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THE PHYSICAL REVIEW

A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

CONDUCTED
WITH THE CO-OPERATION OF THE

AMERICAN PHYSICAL SOCIETY

BY

EDWARD L. NICHOLS

ERNEST MERRITT, and FREDERICK BEDELL

CLIII

DECEMBER, 1908

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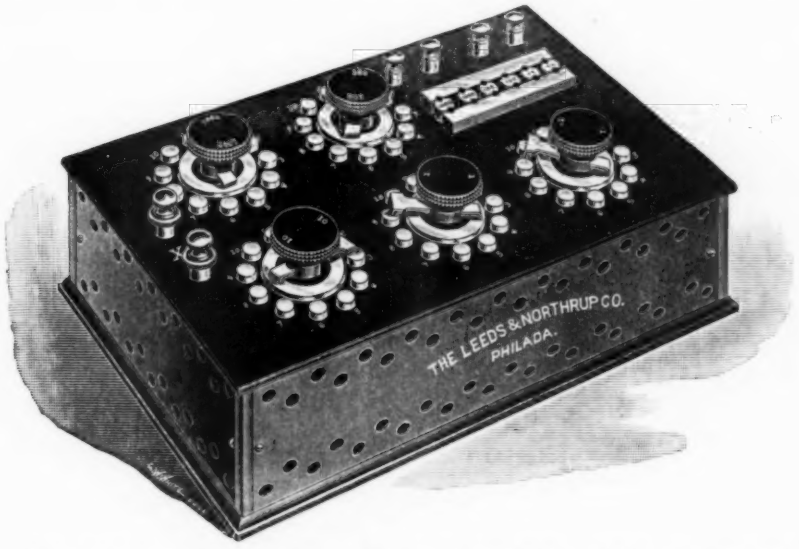

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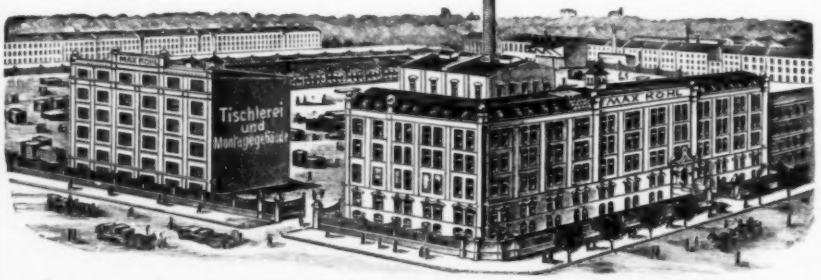

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Volume XXVII. *December, 1908.* *Number 6*

THE

PHYSICAL REVIEW.

THE IONIZATION OF GASES AT HIGH PRESSURES.[1]

By Henry A. Erikson.

THE ionization produced in gases by the different ionizing rays has not heretofore been studied for pressures much greater than one atmosphere.[2] It is of considerable interest, however, to know how the ionization and the rate of recombination of the ions change as the density of the gas becomes considerable and approaches that of the liquid state.

In the experiments to be described the ionization produced by the gamma (γ) rays of radium was studied for pressures up to 400 atmospheres in the case of air, and up to the liquefying point in the case of carbon dioxid.

The results obtained will be presented, after a description of the apparatus, under the following subdivisions:

Results for air:

1. Ionization current at different pressures and potentials.
2. The time required for the rays to produce the steady state.
3. The lingering of the ions.
4. The time required to collect the ions.
5. The ionization current at different temperatures.

Results for carbon dioxid:

1. The lingering of the ions.
2. Ionization current at different pressures and potentials.
3. The natural conductivity of CO_2 at different pressures and temperatures.

[1] Paper presented at the Chicago meeting of the Physical Society, January 1, 1908.

[2] McClung, Phil. Mag., p. 283, Vol. 3, 1902.

4. The ionization current at different temperatures.
Summary and conclusions.

APPARATUS.

A diagram of the apparatus used in the experiments is given in Fig. 1.

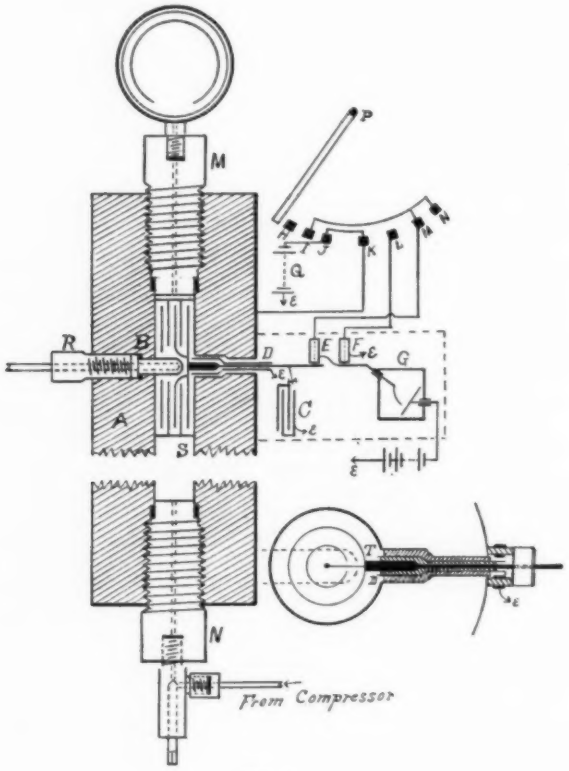

Fig. 1.

A is an iron cylinder 84 centimeters in length and 20.3 centimeters in diameter. Along the axis of the cylinder is a hole *S* 5.1 centimeters in diameter, closed at each end by means of the two steel plugs *M* and *N* which have two threads to the centimeter and are made tight by means of lead packing.

The upper end of the hole *S* is lined with brass and serves as the ionization chamber, the inside dimensions of which are 16.7 centimeters in length and 4.9 centimeters in diameter. The elec-

trodes are made of brass gauze 0.04 centimeter in thickness and are concentric cylinders separated on the average by 0.8 centimeter. The inner cylinder and the lining of the chamber form one electrode and are connected to the iron cylinder A, while the other cylinder and the central wire form the other electrode T, and are insulated from A. The insulated electrode T is supported by a brass rod passing through a hard rubber plug provided with a guard ring D. This brass rod has a shoulder near the inner end and is threaded at the outer end, the nut on which serves to tighten the entire plug, the gas pressure alone on the inside not being sufficient to prevent leakage.

A brass thimble 0.22 centimeter in thickness projects into the ionization chamber at B. This thimble is set in lead packing and is held in place by the hollow, threaded, steel plug R to which is attached axially a slotted metal tube one meter in length.

A metal tube containing the radium salt can be placed inside the thimble and the penetrating gamma rays allowed to ionize the gas in the ionization chamber. The tube of radium may be quickly withdrawn by releasing a stretched spiral spring attached to it.

The insulated electrode T is connected to two McLennan keys E and F and then to the leaf of a Wilson form of gold-leaf electroscope G. C is a condenser of 0.001 microfarad capacity and is used to increase the capacity of the electrode system, the purpose being to decrease the rate of motion of the leaf of the electroscope.

When the iron cylinder is given a potential different from that of the earth, a current begins to flow between the electrodes because of the ions produced in the gas by the gamma rays. If now the electrode T is insulated from the earth by opening the key F, the leaf of the electroscope begins to move and the time t required for its image to pass a given number of divisions on the scale in the eyepiece of the microscope can be determined. Knowing the capacity C' of the electrodes and the potential V necessary to deflect the leaf the given number of divisions, the absolute value of the current may be determined from the relation

$$I = \frac{C' V}{t}.$$

In order to determine the number of ions present in the gas at any instant it is necessary to make a number of connections consecutively. This is accomplished by means of the pendulum P. The arrangement is such that as the pendulum reaches H it shuts off the rays by releasing the spring which withdraws the radium from the cylinder, at I it opens the key E, at J it connects the cylinder to the battery Q, at K it disconnects the battery and connects the cylinder to earth, at L it insulates the leaf of the electroscope, at M it connects the electrode to the electroscope and at N it opens again the key E.

The electroscope was found much more convenient than the quadrant electrometer in this investigation, as the inappreciable inertia of the leaf permits an observation to be repeated very

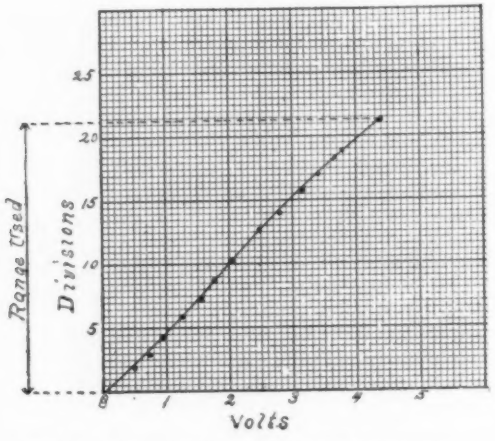

Fig. 2. Sensibility Curve for the Electroscope.

quickly and easily. Fig. 2 gives the calibration curve for the electroscope and shows the range used in the current readings. The same sensibility was used throughout the entire investigation, the sensibility selected being determined by the strength of the currents involved and the magnitude of the charge present in the gas at any instant.

The potential on the plate of the electroscope was obtained from a battery of fifty large lead chloride cells. The potentials of the cylinder up to one thousand volts were obtained from a high poten-

tial storage battery, and potentials higher than one thousand volts were obtained by means of a small static machine in conjunction with a large battery of Leyden jars.

The radioactive substance used was about 0.6 gram of a salt containing 1 per cent. of radium bromide.

Results for Air.

In the case of air, pressures up to two hundred atmospheres were obtained by means of a Whitehead compressor belonging to a liquid air plant and pressures higher than two hundred atmospheres were obtained by means of a Cailletet hand compressor, the liquid used in it being paraffin-oil. The air used was purified by passing through lime before entering the compressor and then after being compressed it was passed through a cylinder containing caustic potash. In a part of the work the air was also passed through a quantity of cotton just before entering the ionization chamber in order to remove any dust that might be present.

Table I.

Ionization Current at Different Potentials and Pressures.

20 Atmos.		40		140		400	
V	*t*	*V*	*t*	*V*	*t*	*V*	*t*
6.0	64.4	6.0	68.2	6.0	92.0	6.0	178.0
10.3	39.4	10.4	38.2	9.9	47.9	10.0	64.5
20.8	27.8	21.0	25.4	20.0	25.7	21.5	34.5
30.6	24.6	30.8	21.7	27.5	21.0	32.0	27.5
41.1	23.2	41.8	19.8	41.5	17.2	45.7	23.9
61.2	21.8	61.8	17.0	61.0	15.0	64.4	19.8
81.8	21.1	82.2	16.2	82.0	13.8	85.2	17.7
102.0	20.6	102.8	16.5	101.0	13.0	106.3	16.4
128.0	20.1	128.0	16.3	128.0	12.7	175.0	14.8
210.0	19.1	210.0	15.2	170.0	12.0	218.0	14.2
290.0	18.4	292.0	14.7	210.0	11.4	300.0	13.6
415.0	17.9	418.0	14.2	290.0	11.1	431.0	12.5
485.0	17.6	490.0	13.8	410.0	10.6	512.0	12.2
606.0	17.3	612.0	13.5	480.0	10.3	621.0	12.2
690.0	16.8	697.0	13.2	600.0	10.1	708.0	12.1
815.0	16.8	822.0	13.1	675.0	9.9	830.0	11.7
900.0	16.5	905.0	13.1	790.0	9.8	912.0	11.6
1020.0	16.5	1030.0	12.7	870.0	9.5	1040.0	11.5
				978.0	9.4		

The Ionization Current at Different Pressures and Potentials.

1. The relation between the current and the voltage was obtained for a large number of pressures. The various voltages were applied to the cylinder and thus to the electrode connected to it, and the time in seconds was taken which was required for the leaf of the electroscope to move a number of divisions equal to the range shown in Fig. 2. The current in any case is proportional to the reciprocal of this time.

To illustrate the nature of the readings a few results are given in Table I.

The results are shown graphically in Fig. 3, where the abscissas represent the voltage and the ordinates the reciprocal of the time. The pressure corresponding to each curve is given at the right.

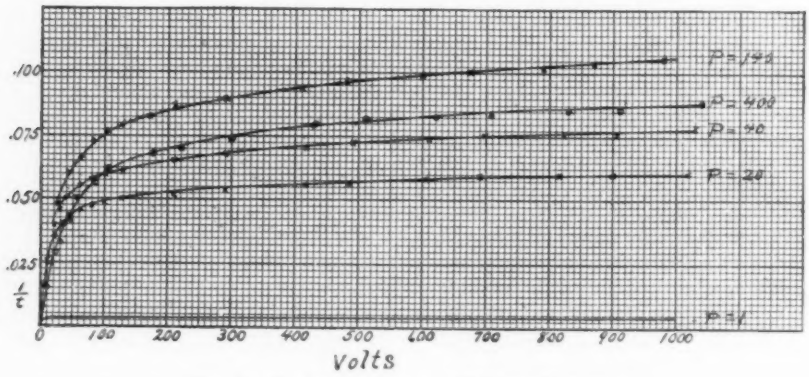

Fig. 3. Ionization Curves at Different Pressures.

It is noticed that the curves for the higher pressures take the general form of the saturation curve at the pressure of one atmosphere, only that after the first rapid increase of the current, they still rise considerably with increase of voltage. In comparing with the curve for one atmosphere, it is seen that at the higher pressures the currents are considerably larger though not proportional to the pressure since at 20 atmospheres the current for 1,000 volts is only about 15 times that at one atmosphere. By doubling the pressure to 40 atmospheres the current increases but 30 per cent., and at 140 atmospheres with a pressure seven times that at 20 atmospheres the current is but 1.8 times as large. Finally, at 400 atmospheres

the current is less than that at 140 and not much above that at 40. With a low voltage the current at 400 atmospheres is seen to be even smaller than that at 20.

Some results which show the relation of the currents at different pressures when small voltages are applied to the electrodes are represented by the curves in Fig. 4. These results were obtained with a different sensibility. As the pressure increases the initial slop

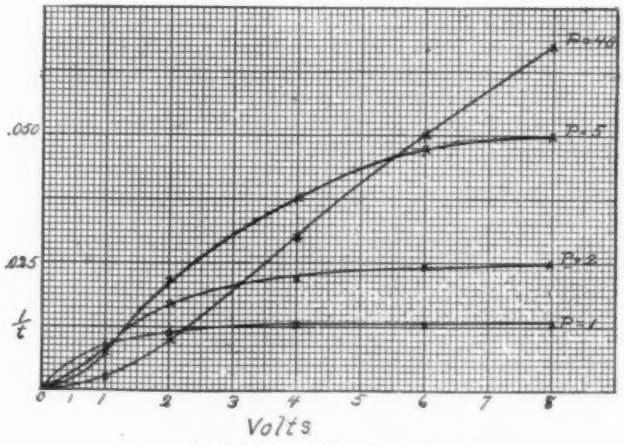

Fig. 4. Initial Slope of the Ionization Curves.

of the curves diminishes. They soon rise however and up to 140 atmospheres intersect all of the curves for lower pressures.

Inasmuch as the current through the gas does not increase regularly with the density of the gas, it is of interest to plot results showing how the current varies with the pressure of the gas when the difference of potential between the electrodes is maintained at a constant value. Table II. gives some results of this kind which were obtained for a number of potentials ranging from 8.3 to 2,500 volts. The initial pressure in each case was 400 atmospheres and readings were taken as the pressure was reduced by steps. The results given for the time in Table II. represent the average of from three to eight separate readings obtained in seconds by means of a stop watch. The potential of the plate of the electroscope was adjusted so that the gold leaf was at zero. The watch was started the instant the key F was opened and when the leaf came to the

end of the range used the watch was stopped. The following is a characteristic set and was obtained for $P = 240$ and $V = 1{,}050$:

9.6, 9.7, 9.6, 9.4.

TABLE II.

Change of the Ionization Current with the Pressure of the Air.

8.3 Volts.		18.7 Volts.		41.5 Volts.		102.0 Volts.		1,050 Volts.		2,500 Volts.	
P	*t*	*P*	*t*	*P*	*t*	*P*	*t*	*P*	*t*	*P*	*t*
400	86.2	401	41.7	400	24.1	400	17.0	400	11.6	400	10.4
390	83.7	390	39.0	390	23.4	391	16.8	391	11.4		
380	82.5	380	38.8	382	23.4	380	16.5	380	11.4	380	10.1
370	83.7	370	38.1	370	23.0	370	16.5	370	11.1		
361	81.3			360	22.9	361	16.0	360	11.1	361	9.7
350	80.0	350	36.4	350	22.7	351	16.0	351	11.0		
340	78.7	340	36.2	341	22.1	342	15.8	340	10.7	341	9.4
331	78.1	330	35.8	331	21.1	332	15.5	330	10.6		
321	78.7	321	33.2	320	21.3	321	15.2	321	10.6	322	9.1
311	77.5	310	34.8	310	21.2	310	15.1	310	10.4		
301	75.0	300	34.1	300	20.8	301	15.0	301	10.2	301	9.1
290	75.0	291	33.7	290	20.4	290	14.7	289	10.1		
282	73.7	282	33.3	280	20.3	281	14.7	280	10.0	284	8.8
271	75.0	271	33.1	270	19.9	271	14.4	270	9.9		
261	71.2	261	32.4	260	19.9	260	14.2	261	9.7	262	8.8
251	70.0	251	31.7	250	19.3	250	14.0	250	9.6	249	8.4
240	67.5	240	31.1	240	19.0	240	13.8	240	9.6		
230	66.2	230	30.5	230	18.8	230	13.7	230	9.6	230	8.2
220	65.0	220	30.1	220	18.7	220	13.5	220	9.3	217	8.2
210	65.0	210	30.0	210	18.5	210	13.4	210	9.3		
201	62.5	200	29.2	200	18.3	200	13.4	200	9.3	201	7.9
190	61.2	190	28.7	190	18.1	193	13.2	191	9.2		
180	62.5	180	28.1	180	17.7	180	13.1	181	9.2	184	7.9
170	60.0	170	27.5	170	17.4	170	12.7	170	9.1	170	7.7
160	57.5	159	27.0	160	17.4	160	12.8	160	9.0		
150	57.5	150	26.6	150	17.2	149	12.6	149	9.0	152	7.7
140	56.2	140	25.9	140	17.2	139	12.7	140	9.1	137	7.8
127	55.0	130	25.8	130	16.8	130	12.6	130	9.1		
117	53.7	120	25.5	120	16.8	119	12.6	120	9.1	120	7.9
110	52.5	110	25.0	110	16.7	110	12.8	110	9.2		
100	51.2	100	24.7	100	16.8	99	12.9	100	9.4	98	8.2
90	50.0	87	24.7	90	16.6	89	13.1	90	9.4		
79	48.7	80	23.9	80	16.7	78	13.2	80	9.8	80	8.6
68	48.7	68	24.1	70	17.0	71	13.5	69	10.0		
58	45.0	60	24.3	60	17.4	59	14.6	57	10.8	60	9.4
50	45.0	50	24.5	50	18.1	50	14.6	50	11.1		
39	46.2	40	25.0	38	19.1	39	16.0	40	12.4	38	10.8
30	43.7	30	25.9	30	20.3	28	18.0	26	14.5		
17	43.7	20	27.7	20	22.3	19	20.2	20	16.0	20	15.0

The current is proportional to the reciprocal of this time. Whenever a redetermination was made the results checked to well within 2 per cent. even though the cylinder had, in the meantime, been emptied of air and then again refilled. Likewise a similar agreement was found to exist when the current-voltage curves (*i. e.*, curves like those shown in Fig. 3) were obtained for any pressure.

The results given in Table II. are shown graphically in Fig. 5.

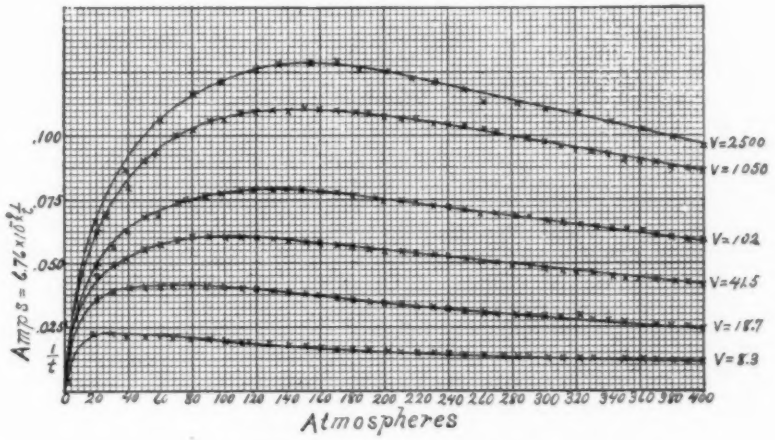

Fig. 5. Currrent-Pressure Curves at Different Potentials.

As the density of the gas is increased there is at first, as was seen before, a marked increase in the current obtained. The current, however, reaches a maximum value and begins to decrease at a pressure depending upon and increasing with the potential between the electrodes. For 1,050 volts the maximum is at about 150 atmospheres.

With the higher potentials, for all pressures somewhat higher than those giving the maximum current, the curves are straight lines; that is, the current is an inverse linear function of the density. This decrease in the current when the pressure of the gas is increased can hardly be attributed to a decrease in the number of ions produced by the rays but rather, in the case of a small difference of potential between the electrodes, to a decrease with pressure of the velocity of the ions thus permitting a greater loss by recombination. This loss more than offsets the increase in the current due to

decrease with pressure of the rate of recombination, a fact to be brought out later in this paper.

In the case of the higher potentials the decrease of the current is undoubtedly due, in a large measure at least, to an initial recombination; that is, the return of a newly formed electron to its parent atom, the existence of which was suggested by Rutherford[1] and by Bragg and Kleeman.[2] Since the current decreases when the density of the gas is increased the nearness of the molecules must play an important part in this initial recombination, and it is quite probable that the currents shown in Fig. 5 for the potentials 1,050 and 2,500 include all of the free ions (*i. e.*, ions which have been projected beyond the influence of their former associate) produced by the rays and that the difference between the two curves is due mainly to those ions which without the aid of the field, due to the potential between the electrodes, would not become separated.

The Time Required for the Rays to Produce a Steady State.

2. When the rays begin to act upon a gas under a high pressure it takes an appreciable time before the number of ions in the gas

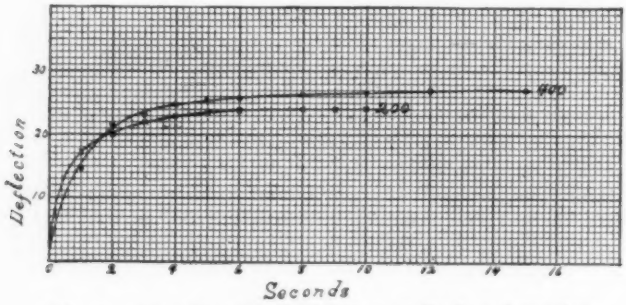

Fig. 6. Time Required for the Rays to Produce Saturation.

reaches a steady value, the rate of production being greater than the rate of recombination until the steady state is attained. The greater the pressure the longer is the time required.

Results illustrating this, for pressures of 200 and 400 atmospheres, are given in Fig. 6 where the ordinates are proportional to the number of ions collected after the rays have acted upon the gas an

[1] Radioactivity, p. 33.

[2] Phil. Mag., Vol. II., p. 466, 1906.

interval represented in seconds by the abscissas, the difference of potential used being 1,000 volts.

It will be seen that at 200 atmospheres it takes about eight seconds before the ions in the gas reach a maximum number, whereas at 400 atmospheres it requires about fourteen seconds.

The Lingering of the Ions.

3. As the density of the gas increases the readiness with which the free ions recombine diminishes to a marked extent, so that some of the ions linger for some time before they recombine. The results of some experiments on this point are shown in Fig. 7.

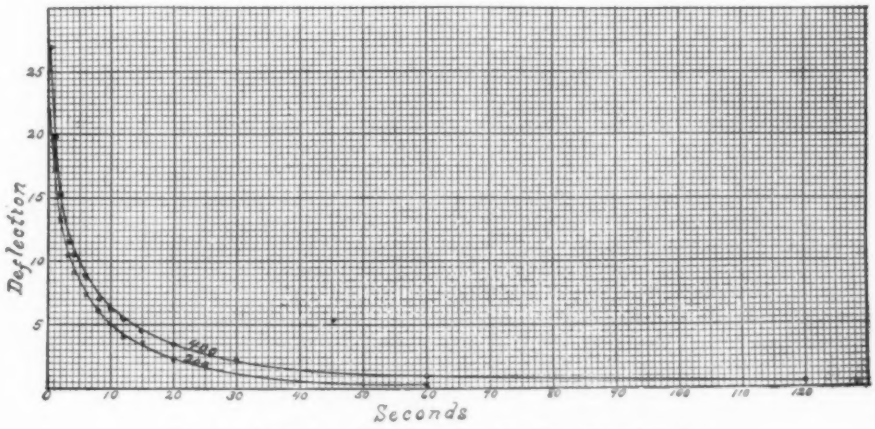

Fig. 7. Lingering of the Ions after the Rays Ceased to Act.

The gas was exposed to the rays for a length of time sufficient to produce the maximum number of ions. The rays were then discontinued and after a measured interval of time, a potential of 1,000 volts was applied to the electrodes and the deflection of the leaf due to the charge acquired by the electrodes was measured. The deflection in this case is proportional to the charge and is represented by the ordinates in Fig. 7, the time interval being represented in seconds by the abscissas. The pressures used were 200 and 400 atmospheres as indicated on the curves. It will be seen that at 200 atmospheres an appreciable number of ions were still uncombined sixty seconds after the rays had been discontinued and that at 400 atmospheres there were still uncombined ions at the end of 120 seconds.

The lingering of the ions is further illustrated together with their slowness of motion in an electrical field, by the results represented in Fig. 8, where the ordinates are proportional to the number of ions obtained at 195 atmospheres with a potential of 1,090 volts, after the rays had ceased to act upon the gas for a time represented in seconds by the abscissas, the electrodes during this whole interval having the difference of potential given at the end of the curves. Thus even with a constant difference of potential of 41.5 volts acting, there are still an appreciable number of ions present three seconds after the rays ceased to act.

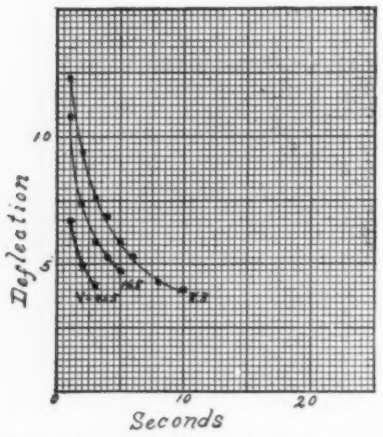

Fig. 8. Motion of the Ions in a Weak Electric Field.

The Time Required to Collect the Ions.

4. The slowness with which the ions are drawn to the electrodes is shown further by the curve in Fig. 9, which gives the charge obtained, with the field acting for different times, just after the rays had ceased to act, the pressure being 200 atmospheres, the potential 1,000 volts and the distance between the electrodes 8 mm.

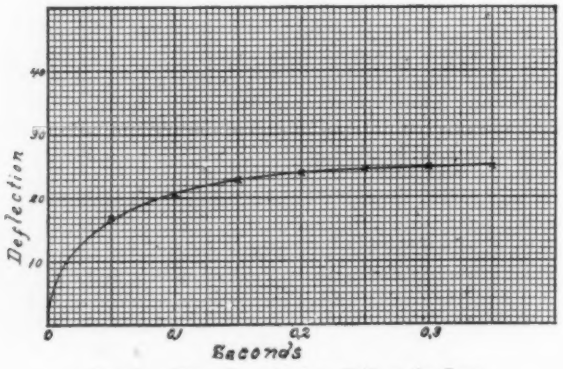

Fig. 9. Time Required to Collect the Ions.

It is seen that in this case it requires about three tenths of a second for all of the ions to get to the electrodes.

The Ionization Current at Different Temperatures.

5. An increase in the temperature of the air at high pressures causes a change in the ionization current, and in the number of ions collected when the rays have ceased to act and a voltage is applied to the electrodes.

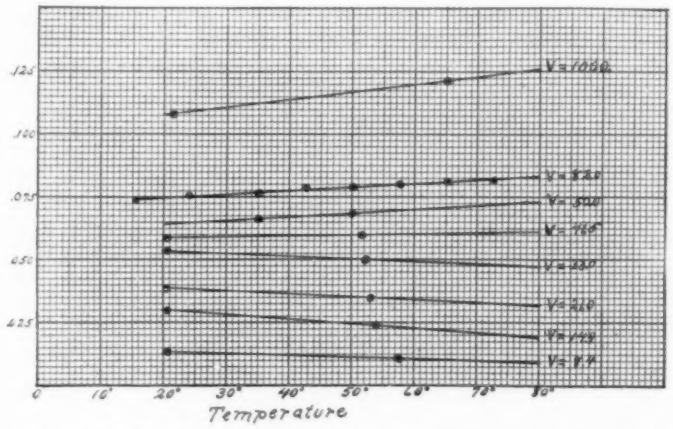

Fig. 10. Ionization Current at Different Temperatures and Potentials.

The results of some experiments along this line are shown in Fig. 10 where the ordinates of the curves are proportional to currents obtained at the various temperature represented by the abscissas when the constant voltages given in each case were applied to the electrodes, the density of the gas being kept constant, the pressure at 20° being 200 atmospheres. It is seen that with the smaller voltages the curves slope downward while for the higher potentials they slope upward. With a difference of potential of about 38 volts there would be no change in the current as the temperature of the gas is increased.

The change in the number of ions that are drawn to the electrodes, after the rays have been removed, at two different temperatures is shown in Fig. 11. The ordinate represented by A is proportional to the number of ions drawn to the electrodes when a difference of potential of 1,000 volts was applied, one tenth of a

second after the rays ceased to act, the temperature being 21° Centigrade and the pressure of the gas 200 atmospheres. B is proportional to the number obtained four seconds after the rays ceased to act, the temperature and pressure being the same as for A. C and D are corresponding points at a temperature of 43°, the density of the gas being the same as for A and B. It is seen that more ions are drawn to the electrodes, one tenth of a second after the rays ceased to act, at the higher temperature than at the lower. After an interval of four seconds, however, the number is practically the same at both temperatures.

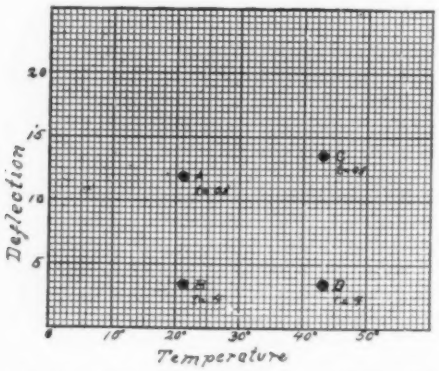

Fig. 11. Number of Free Ions Produced at Different Temperatures.

The fact that the upper curve in Fig. 10 has an upward slope and that C in Fig. 11 represents a greater charge than A indicates that at the higher temperature a greater number of free ions are produced by the rays, and since the difference between C and D is greater than that between A and B there is at the higher temperature a more rapid recombination, an interpretation that is however subject to the great uncertainty as to the part played by diffusion.

The two last above-mentioned changes are opposite in their effect on the ionization current and it seems reasonable to suppose that the potential 38, see Fig. 10, for which there is no change in the current with temperature, establishes a condition such that the increase in the number of free ions is just offset by the greater loss due to the increase of the rate of recombination. At potentials less

than this the time required for the ions to pass to the electrodes is greater and therefore there is a greater loss by recombination and a consequent decrease in the current. At higher potentials, however, the time is shorter so that there is a smaller loss due to recombination and therefore an increase in the current.

There are indications, however, that at 38 volts the current remains constant only for a short range of temperature and that the curve soon begins to turn downward. This will be brought out in a subsequent paper.

No determination of the change with temperature of the ionic velocity due to the field has yet been undertaken. A change of this kind would have no effect at the higher potentials where practically all the ions are drawn to the electrodes so that there is no loss due to recombination. At lower potentials it would affect somewhat the slope of the current-temperature curves. The general character of the curves shown in Fig. 10 is, however, independent of a change of this kind.

Results for Carbon Dioxid.

The results given below were obtained with commercial carbon dioxid, for pressures up to the liquid state. The method employed for filling the ionization chamber with carbon dioxid was as follows: The supply cylinder containing the liquid CO_2 was inverted and placed higher than the testing cylinder. It was allowed to remain in this position for some time, so as to permit any free light impurities to rise to the top of the liquid and any heavy impurity to sink to the bottom. Before filling the ionization chamber the liquid was allowed to escape into the air for a time sufficient to force out any heavy impurity which might have collected near the outlet at the bottom of the cylinder.

The Lingering of the Ions in Carbon Dioxid.

1. The results for the lingering of the ions in carbon dioxid at 61 atmospheres pressure and at a temperature of 21° C. are shown in Fig. 12.

Here again the ordinates are proportional to the number of ions present, at times after the rays had ceased to act, which are

expressed in seconds by the corresponding abscissas. The lingering is here much more marked than in air at the same pressure, doubtless owing to the greater density, the amount being comparable to that for air at 400 atmospheres.

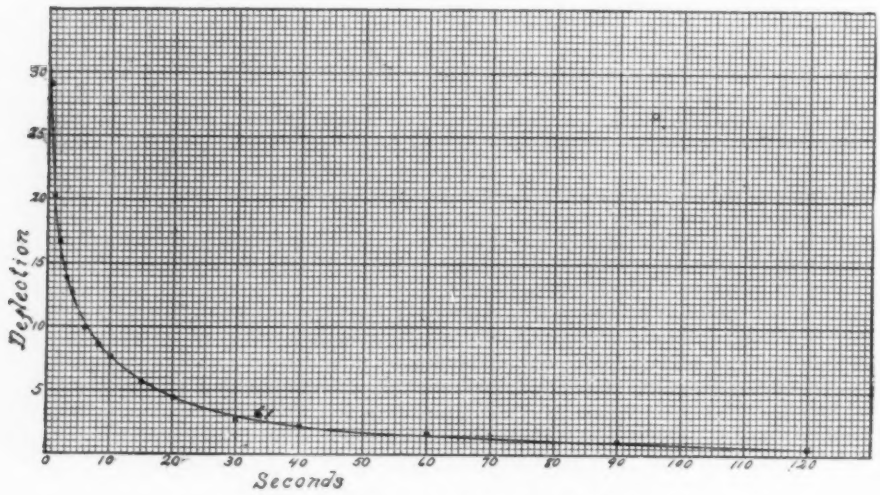

Fig. 12. Lingering of the Ions in Carbon Dioxid.

The Ionization Current at Different Pressures and Potentials.

2. The relation between the pressure and the current due to the ions produced by the gamma rays was determined for a number of potentials. The results obtained for the time t at the various potentials and pressures are given in Table III. At the higher pressures there is an appreciable natural conductivity in the gas. This in itself gives rise to a current which is present when the rays are acting. The time for the current due to the rays alone was calculated by taking the product of the time due to the natural current alone and the time for the two currents together and dividing this by the difference of the two times.

These results are shown graphically in Fig. 13 by the curves marked with crosses, where the ordinates are proportional to the currents and the abscissas represent pressures up to 65 atmospheres where the gas became liquefied. The potential corresponding to each curve is given at the right.

TABLE III.

Change of the Ionization Current with the Pressure of CO_2.

8.5 Volts.		21 Volts.		41.5 Volts.		102 Volts.		1,040 Volts.	
P	*t*	*P*	*t*	*P*	*t*	*P*	*t*	*P*	*t*
6	5.56	6	41.2	6	35.52	6	32.6	6	27.5
10		10	34.7	10	29.0	10	26.2	10	21.3
15	56.52	15	31.1	15	25.9	15	22.4	15	17.2
20		20	28.1	20	22.0	20	19.0	20	15.8
25	55.0	25	27.6	25	20.7	25	17.7	25	12.5
30	57.3	30	26.8	30	19.7	30	16.1	30	12.9
35	58.7	35	26.9	35	19.7	35	15.6	35	12.2
40	64.5	40	27.1	40	19.0	40	14.6	40	11.4
45	62.7	45	26.8	45	18.6	45	14.1	45	10.8
50	68.1	50	27.7	50	18.7	50	14.3	50	10.7
55	70.5	55	28.5	55	18.7	55	13.8	55	9.9
60	84.6	60	31.9	60	19.7	60	13.5	60	9.3
64	91.0	64	33.3	64	20.6	64	13.7	64	9.2

It is is seen that the curves are in general similar to those for air. This indicates that the ionization is independent in a large measure at least of the intermolecular forces which exert a large influence upon the gas when it approaches the liquid state.

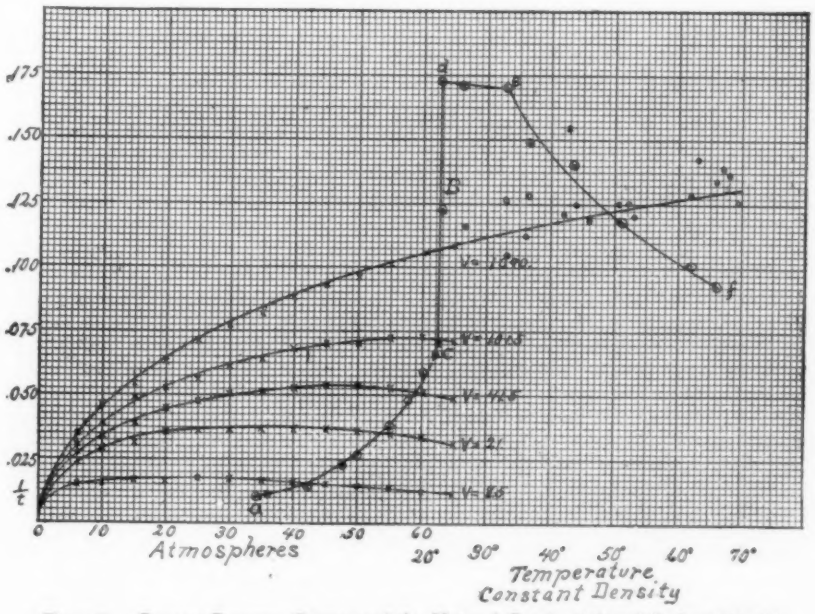

Fig. 13. Current-Pressure Curves and the Natural Conductivity of Carbon Dioxid.

The Natural Conductivity of Carbon Dioxid.

3. Some results showing how the current due to the natural conductivity of the CO_2 changes with the pressure of the gas are represented by curve *B* in Fig. 13, the difference of potential used being 1,000 volts. The first portion of the curve from *a* to *c* shows how the natural conductivity increases as the gas approaches the liquid state. There is a very sudden increase *cd* in the conductivity at 62.5 atmospheres which is the pressure at which the CO_2 liquefies for the temperature involved; namely, 22.6° C. At this stage when the cylinder had become filled with the liquid the lower valve was closed so that the density could not change. Heat was then applied to the outside of the cylinder and readings for the current were taken as the temperature slowly increased. The results are shown by the portion *def* of curve *B*, where the abscissas now represent temperatures instead of pressures, the ordinates as before being proportional to the current due to the natural conductivity. It is seen that the conductivity decreases slowly with the rise in temperature up to about 33° C., above which however it diminishes rapidly. It is to be noticed that this change in the behavior of the liquid takes place at the critical temperature.

The Ionization Current at Different Temperatures.

4. The ionization current due to the rays was also obtained in this range of temperature, the density remaining constant. The results represented by the extended portion of the current pressure curve at 1,070 volts in Fig. 13, indicates that the current undergoes no marked change, the current increasing slowly with the rise in temperature. The fluctuation of the readings was due to inaccuracy in measuring the short time interval (about two seconds) required for the leaf of the electroscope to move through the range used, the available capacity being too small.

These results show that the ionization due to the rays is, at least for the sensibility and potential involved in this investigation, quite independent of the natural dissociation to which the liquid or vapor conductivity is due.

Summary and Conclusions.

The results obtained in this investigation and the conclusions drawn from them are as follows:

(*a*) As the density of air or CO_2 increases, the ionization current obtained with any given potential attains a maximum value and then diminishes. See Figs. 3 and 5. The higher the potential the greater is the value of the density giving the maximum current. At potentials higher than 100 volts the current, beyond the maximum point, is an inverse linear function of the density. A probable explanation of these results is that when the molecules are closer together it becomes more difficult to prevent an electron from returning to its parent atom.

(*b*) It requires several seconds at the higher densities for the rays to produce a steady state. See Fig. 6.

(*c*) As the density of a gas increases the ions linger for a longer time before they recombine, showing that after an ion becomes free it is more difficult for it to combine with another ion when the density of the gas is considerable. See Figs. 7, 8 and 12.

(*d*) The rate of recombination of the ions increases as the temperature of the gas increases. See Fig. 11.

(*e*) The number of free ions produced by the rays increases with the temperature. See Figs. 10 and 11.

(*f*) The natural conductivity of CO_2 gas increases as the gas approaches the liquefying pressure. When the gas liquefies its conductivity suddenly changes to more than double its former value. See *acd*, Fig. 13.

(*g*) The natural conductivity of liquid CO_2 decreases slowly with increasing temperature up to about the critical temperature when it begins to decrease rapidly. See *def*, Fig. 13.

(*h*) The ionization produced by the rays is quite independent of the changes CO_2 undergoes when it liquefies and when it passes through the critical temperature and pressure. See Fig. 13.

In conclusion I wish to express my sincere thanks to Prof. John Zeleny for many helpful suggestions and to Dean F. S. Jones for kindly securing for me the necessary apparatus.

Physical Laboratory,
University of Minnesota,
July 15, 1908.

ON THE SUPPOSED EXCESS OF NEGATIVE ELECTRIFICATION PRODUCED BY SPRAYING.

BY J. C. POMEROY.

ALLESANDRINI and others[1] have shown that when water is broken up into a fine spray ionization is produced. Eve[2] found the number of negative and positive ions to be in the ratio of 4 to 3 and the following investigation was undertaken in an attempt to find the explanation of this discrepancy.

A Gouy sprayer, as shown in Fig. 1, was used. The air passed

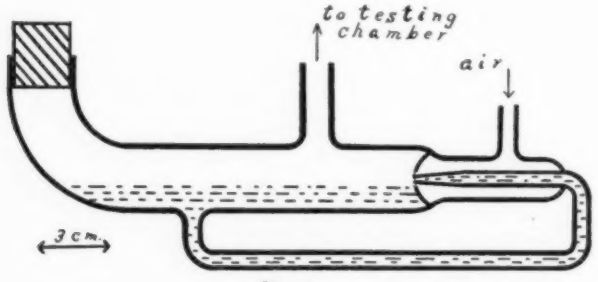

Fig. 1.

from the sprayer into the testing chamber of an ordinary two-chambered electroscope as shown (to scale) in Fig. 2. A rather small gold leaf, charged to about 250 volts, was used and observed by a microscope.

All readings are given with the natural leak deducted whenever this was appreciable and they are generally averages of a number of observations.

A fairly steady air current was obtained by using an ordinary glass-blower's bellows run by a motor. The air pressure was regulated as shown in Fig. 3. The air was first pumped into a large carboy *c* from which it passed to the sprayer through a glass wool-filter *f* (to remove dust and possible ions). A side tube *a* dipped

[1] E. Allesandrini, N. Cimento, 4, p. 389, December, 1902. H. A. Wilson, Phil. Mag., July, 1902. A. S. Eve, Phil. Mag., September, 1907, p. 382.

[2] Eve, loc. cit.

about 80 cm. into a cylinder of water *b* and the motor was run at such a rate that the air constantly escaped through this tube.

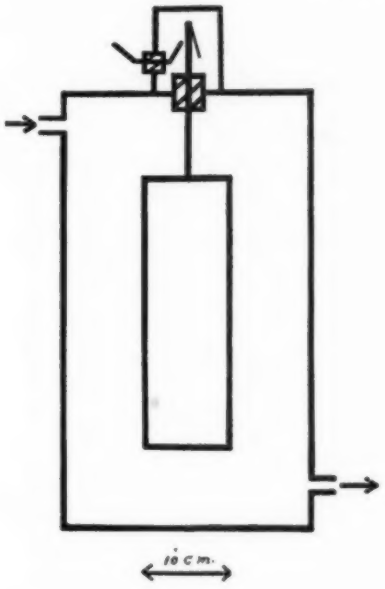

Fig. 2.

When the sprayer contained no water the passage of air through the apparatus produced no effect on the electroscope, whether positively or negatively charged.

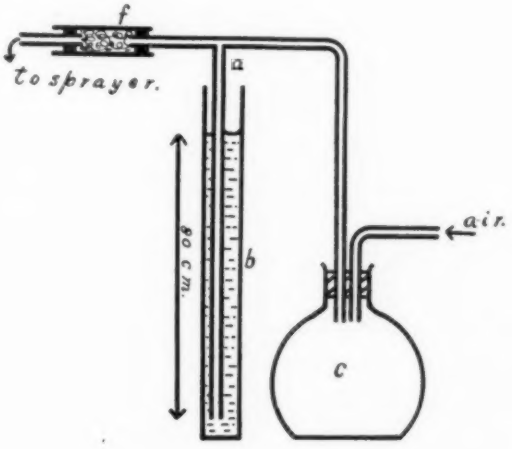

Fig. 3.

Eve first charged his electroscope and then pumped air through the sprayer into the testing chamber for one fourth or one half minute. He found no indication of a difference in the velocity of the positive and negative ions.

In this investigation three slightly different procedures were followed :

1. Eve's method of first charging the electroscope and then pumping for one fourth minute and measuring the fall of the gold leaf at stated periods.

2. The electroscope was first charged and the rate of leak for steady pumping was measured.

3. The electroscope was, at first, left uncharged and the air-current continued for two minutes or until a steady state was obtained in the testing chamber. The air was then suddenly stopped, the electroscope quickly charged and the fall of the leaf timed.

The results by each of the three methods show, as Eve's did, an excess of negative ions, the ratio, being approximately 3 to 2. The first and second methods gave no indication of different velocities for the positive and negative ions as the ions of both signs were removed almost as fast as they entered the testing chamber. This was shown by there being very little fall of the leaf after the air-current was cut off. Table I. gives the average of a number of readings by the third method.

TABLE I.

		First Quarter Min.	Second Quarter Min.	Second Half Min.	Second Min.	Total Fall.
Fall of gold leaf in microscope scale divisions.	+ ions.	8	2	1	0	11
	— ions.	14	3	1	0	18
Percentage of total fall.	+ ions.	72.7	18.2	9.1	0	
	— ions.	77.8	16.7	5.6	0	

From the above table it will be noticed that a larger percentage of the negative, than of the positive ions was removed by the field during the first quarter minute after stopping the air current and putting on the field, while the reverse is the case in the second quarter and second half minutes. This indicates a somewhat greater velocity for the negative ions as they are removed more rapidly. The difference is small but was noticeable in each of the readings taken.

Both positive and negative ions were found to be entirely removed by a filter,[1] consisting of a cylindrical metal box (6.5 cm. × 6.5 cm.) filled with glass wool and insulated by quartz tubes through which the air passed in and out. This box was connected to a Dolezalek electrometer and with constant spraying the needle moved uniformly at about 100 graduations per second until it passed off the scale in a direction indicating a negative charge. Whenever the air was abruptly stopped the needle remained at its maximum position except for a slight natural leak. As the glass wool catches all the ions of both signs the chamber acts as a "Faraday box" and the result proves an excess of negative electrification on the incoming air and spray.

Having then found that the air and spray entering the electroscope really carried more negative than positive electricity the next point was to trace this disparity to its source. To do this a different form of sprayer was employed (see Fig. 4).

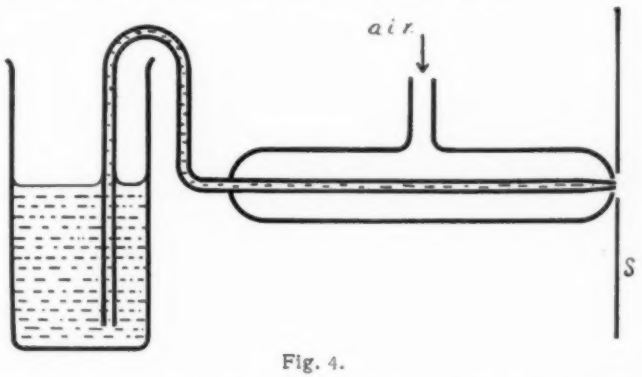

Fig. 4.

Reservoir and sprayer (see figure) were carefully insulated and connected to the electrometer but no charge was found even with continued spraying. A grounded metallic screen *s* was then placed in front of the sprayer so that air and spray passed through a hole in its center. This screen was designed to prevent ions from the spray being drawn back onto the sprayer and thus neutralizing any charge it might acquire. It also prevented air currents carrying ions back onto the sprayer and thus charging it. As no movement of the electrometer needle was obtained in either of these cases this disposes of the idea that any part of the positive electrification was

[1] Compare Eve, Phil. Mag., September, 1907, p. 384.

left on the sprayer. This result made it probable that positive electricity was carried out of the spray by the heavier drops that were not carried along by the air current.

This idea was tested as follows: a metal pan (30 cm. by 10 cm.), insulated and connected to the electrometer, was so placed that a large part of the heavier spray settled on it. Under these conditions the electrometer needle moved at 20 graduations per second, indicating a steadily increasing positive charge brought there by the heavier spray.

To make sure that this was not due to the splashing of the water particles against the metal surface[1] the pan was partly filled with water but this did not appreciably affect the rate at which the electrometer moved. If Lenard's "double layer of electrification" theory is to hold or if the electrification due to splashing is caused in *any* way by a change in the area of the water surface then it seems that any possible effect due to splashing should be of opposite sign in these two cases, since in the first there is an increase in the water surface when a particle strikes and in the second a decrease.

In the next place a metal shield was placed over the pan and connected with it, as in *s*, Fig. 5, so that the greater part of the air and spray would be directed by the shield into the pan. The needle moved *slowly* to a *maximum* of 23 graduations in a negative direction, attaining this in about 10 seconds whether the pan contained water or not. That is, when both air and spray came in contact with the collector the charge proved to be much smaller than when the heavier drops alone were caught.

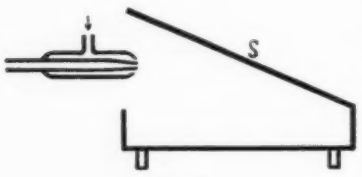

Fig. 5.

These facts and the non-electrification of the sprayer itself tended to confirm the idea that the heavier spray carried part of the positive electrification out of the field and left the air and lighter spray with an excess of negative ions.

Following out the above crude experiments, a testing vessel was constructed, which consisted of a bent tube of three insulated sections, as shown in Fig. 6. The end of the sprayer was cemented into the end of section *I*, so as to ensure all the air and spray pass-

[1] See Lenard, Wied. Ann., XVLI., 1892, p. 584.

ing through the chamber. Each section was insulated from the next so that each, in turn, could be connected with the electrometer or could be grounded. A plug of glass wool similar to one which had before been proved to stop all ions was placed in the end of section *III*. On grounding two sections and connecting the other to the electrometer continuous spraying caused the needle to move *slowly* to a maximum deflection, which it reached in from four

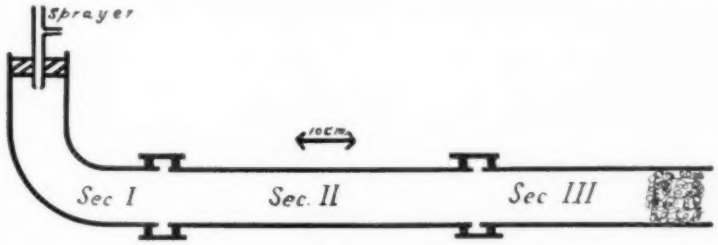

Fig. 6.

to six minutes. When section *I*, in which most of the heavier particles were stopped, was connected to the electrometer the needle indicated a *positive* charge with a maximum of 30 scale divisions. When *II* and *III* were tested in the same way the electrometer indicated negative charges of maxima, 25 and 12 scale divisions respectively.

It is well to note, however, (1) that, as the capacities of the three sections were not equal, we are not justified in considering the potentials as indicated by the electrometer in the three cases as proportional to the charges; (2) that the ions were not driven to the sides of the vessel by a field but that the charge indicated by the electrometer, in each case, was merely that due to the excess of the ions of one kind over those of the other in each section at any particular time; (3) that this was measured by its induction (Faraday box) effect; and hence (4) the excess of the sum of the negative readings in *II* and *III* over the positive in *I* is not to be taken as showing an excess of negative electrifications leaving the sprayer.

When the three sections were connected together — thus catching all the ions, positive and negative — the electrometer showed no charge although the spraying was continued for over twenty minutes. This proves that the mixed spray and air, on leaving the sprayer, shows no excess of negative electrification.

The experiment in which the heavier spray was found to carry down so much positive electricity and the difference in the velocities of the positive and negative ions suggested that all the water particles, coarser and finer, might carry positive charges and that. in this case, the negative ions might be attached to clusters of air molecules.

To test this the sprayer shown in Fig. 1 was again used and the air current was kept constant while the measurements were being taken. The air and fine spray were passed from end to end of a rectangular glass vessel (45 cm. × 4 cm. × 4 cm.) to the testing chamber of the electroscope and to a second chamber containing an hygrometer. The top of the rectangular glass vessel consisted of a metal plate attached and insulated with sealing wax. This vessel was sometimes used empty of liquid and, sometimes, with a layer of sulphuric acid covering the bottom. This acid was connected to the ground by a platinum wire dipping into it. The metal plate was sometimes grounded and sometimes charged to a positive or negative potential of between 3,000 and 4,000 volts.

Table II. shows the ionization (positive and negative) reaching the electroscope when the plate was grounded and the vessel contained (1) air only and (2) a layer of sulphuric acid 0.5 cm. deep covering the bottom and connected to the ground. The readings given show the position of the gold leaf at the times indicated, also the differences, giving the fall during successive minutes.

TABLE II.

Time in Minutes.	0	1	2	3	4	5	6
Without acid, + ions	1.1	1.5	2.3	3.3	4.3	5.3	6.3
Difference for 1 minute		.4	.8	1.0	1.0	1.0	1.0
With acid, + ions	1.0	1.3	1.5	1.9	2.3	2.8	3.3
Difference for 1 minute		.3	.2	.4	.4	.5	.5
Without acid, — ions	1.0	2.1	3.4	4.5	5.6	6.7	7.8
Difference for 1 minute		1.1	1.3	1.1	1.1	1.1	1.1
With acid, — ions	1.0	1.8	3.0	4.1	5.3	6.5	7.8
Difference for 1 minute		.8	1.2	1.1	1.2	1.2	1.3

The above table shows that, even when no field was maintained between the acid and the metal plate, fully one half of the positive ions were removed with the water absorbed by the acid, while *the negative ionization was not affected by the presence of the acid.*

Further, when the upper plate was kept charged to a potential of from 3,000 to 4,000 volts all the ions, positive and negative, were removed before reaching the electroscope.

Table III. gives observations on the *dew point* after passing through the above vessel under various conditions. Between each two successive readings a strong current of air was passed through the apparatus (except the sprayer) for five minutes in order to ensure the same initial conditions for each reading.

TABLE III.

	Dew Point.	Approximate Time Taken to Reach Constant Value.
Without acid.		
Plate grounded	14.9° C.	8 minutes.
Plate negative	14.9° C.	20 "
Plate positive	14.9° C.	20 "
With acid.		
Plate grounded	5.1° C.	8 "
Plate negative	5.9° C.	17 "
Plate positive	2.5° C.	10 "

In the above table the following points should be noted:

1. When there was no acid in the vessel the final dew point was not affected by the charge on the plate, the difference between the three average readings obtained being less than 0°.1 C.

2. When the vessel contained a layer of acid and when the plate was grounded the dew point fell to considerably less than one half its former value. This harmonizes with the loss of positive ionization under the same conditions as noted above.

3. When the positive ions were drawn away from the acid by a negative charge on the plate, the final dew point was considerably higher than in the case where there was no electrostatic field between the acid and plate.

4. In the last case (plate positive) the exact dew point was very difficult to determine as almost immediately after the first appearance of moisture, hoar frost formed and this did not disappear until the temperature was considerably above the point at which the moisture first appeared. Hence the value given is probably too high. Thus in this case nearly all the moisture was driven into the acid by the field. This confirms the idea that even the finest spray carried positive charges.

The time taken for the moisture to get into a steady state seems to be an important point. When the positive ions were drawn to a surface from which the moisture can readily evaporate the dew point falls rapidly for a short time then gradually rises taking about twenty minutes to come to a constant value. When, however, there is no field or when the field tends to drive the positive ions to the surface of the acid this time is only one half as great.

This indicates clearly that the fine water particles are positively electrified. They seem to be drawn by a negative charge out of the air, onto the plate for a time but as soon as the quantity of moisture on the plate becomes sufficient to make the evaporation equal to the amount deposited the moisture attained the same value it would have had without the field. When, however, the vessel contained acid and when the positive ions were driven to the surface of the acid the water was absorbed and the moisture did not rise to the value it had without the field. In fact, in this case it did not rise above the minimum value, which it reached in less than ten minutes. But on the other hand when the positive ions were drawn away from the surface of the acid by the field the final dew point was higher than it would have been without the field.

These results tend to show that almost all, if not all, the positive ions due to spraying are on the water particles and that by far the greater part of the water particles carry positive charges. Also, since, when the negative carriers were driven against the acid by the field and the positive ones lifted off it the air is distinctly moister than with no field, the conviction is forced on one, that the negative charges cannot be associated with spray particles to anything like the same extent that the positive ones are, if indeed at all.

This view suggests a possible explanation of the different condensing powers of the positive and negative ions in adiabatic expansions, as investigated by C. T. R. Wilson and others [1] also in the action of ionized air in condensing a steam jet as noted by Helmholtz [2] and J. J. Thompson.[3] If the water particles in the air carry positive, rather

[1] J. J. Thompson, Phil. Mag., Vol. 46, p. 528, 1898; C. T. R. Wilson, Phil. Trans., Vol. 189, p. 265, 1897; Vol. 193, p. 289, 1900; Phil. Mag., Vol. 7, p. 681, 1904. H. A. Wilson, Phil. Mag., Vol. 5, p. 433, 1903.

[2] Helmholtz, Wied. Ann., XXXIII., p. 1, 1887.

[3] J. J Thompson, Phil. Mag., Vol. 146, 528, 1898.

than negative charges they would tend to combine with the negative ions produced by Röntgen rays or other means and only those particles which were uncharged or charged negatively would readily unite with the positive ions.

The objection might be raised that in general no ionization is produced by evaporation.[1] However, Holmgren[2] has shown that electrification is produced even by ripples on the surface of water. In the Wilson apparatus, as there must always be a certain jarring in making the expansion, even if the water is not intentionally shaken up to saturate the air with moisture, the water particles probably carry positive charges as noticed by Aitken[3] and in the production of steam in a boiler, there is always quite sufficient jarring and bubbling to produce ionization. So it seems quite possible that the Wilson and Helmholtz effects referred to above are due, in some measure, to the positive charges carried by the water vapor.

The above investigation was carried out in the Physics Laboratories of Queen's University, at the suggestion of Professor W. C. Baker, and I wish to take this opportunity of expressing my sincere thanks to him for his advice and enthusiastic encouragement and also to thank Mr. C. H. Burroughs for assistance in making the drawings.

[1] Eve, Phil. Mag., September, 1907, p. 382.

[2] Holmgren, Societe Physiographique de Lond., 1894.

[3] Aitken has noticed that when the water in his dust-counting apparatus was allowed to splash about many nuclei were produced. See Edin. Trans., Vol. 35, p. 17, 1890.

SOME PHYSICAL PROPERTIES OF CURRENT BEARING MATTER.[1] V.: REFRACTIVE INDEX.

BY PAUL R. HEYL.

THIS article describes some experiments on the effect of a current of electricity upon the refractive index of copper. The result is negative. With electrolytic copper and sodium light, using a current density of about 50 amperes per square centimeter, there is no change in the index as great as two per cent. The method used was that of Drude, the measurement of the elliptic polarization introduced when plane polarized light is reflected from a polished metallic surface.[2]

For an electrolyte, this question has been investigated by Roiti,[3] Zecher[4] and, to a great degree of accuracy, by Rayleigh.[5] The latter used an interference method, and working with dilute sulphuric acid he was able to state that for a current density of one ampere per square centimeter there could be no change in the index as great as one part in thirteen million. The only work bearing even indirectly upon the question of a metallic conductor, so far as I am aware, is by Laue and Martens.[6] This work, published while the present experiments were still unfinished, had a somewhat different object. More extended reference will be made to it later.

To determine the refractive index of a metal by Drude's method it is necessary to measure Δ, the difference of phase introduced by reflection, and ψ, the azimuth of restored polarization after the light has passed through the compensator. Then the index n is given by the equation

[1] Earlier articles appeared in PHYSICAL REVIEW, XIX., 4; XXI., 3, and XXV., 5.

[2] Drude, Theory of Optics (Mann and Millikan's translation), pp. 255–258 and 361–363.

[3] Pogg. Ann., 150, p. 164.

[4] Repertorium der Physik, 20, p. 151, 1884.

[5] B. A. Report, 1888, pp. 339–360.

[6] Phys. Zeitschrift, vol. 8, no. 23, Nov. 15, 1907.

$$n = \sin\varphi \tan\varphi \frac{\cos 2\psi}{1 + \cos \Delta \sin 2\psi}$$

where φ stands for the angle of incidence of plane polarized light.

In Drude's original experiments[1] the apparatus used was a spectrometer whose collimator and telescope were fitted with nicols, and whose telescope carried in addition, in front of the nicol, a Soleil-Babinet compensator, composed of two quartz wedges and one quartz plate. The same form of apparatus was used in the present work, and the method of following out the experiments was in the main copied closely after Drude. Certain exceptions to this will be explicitly mentioned. The notation here used is that of Drude.

The copper mirror used was prepared by depositing copper electrolytically upon a piece of thin sheet copper until the whole was about a millimeter thick. The electrolytic side of this was then polished, and used for the experiments. The piece used was 2 cm. square, but not all of this was allowed to reflect light into the telescope. Bits of black paper were pasted over those parts where the polish was poorest, so that the measurements might be made to the best advantage. This mirror was mounted at the center of the spectrometer so that it could be rotated in its own plane. The source of light was a bead of sodium carbonate in a Bunsen flame, placed as close to the slit of the collimator as practicable. The setting of the nicols to extinction is not very accurate at the best, and requires as bright a light as possible.

The compensator was calibrated by means of plane polarized light, and it was found that a difference of phase 2π was introduced by 9.95 turns of the milled head. Hence to reduce compensator readings, denoted here by C, to circular measure it is necessary to multiply by 36.18. The zero point of the compensator was determined at each setting, and was found to vary slightly from day to day, probably on account of change of temperature. The extreme variation was from -0.55 to -0.52. In using the compensator to determine Δ four settings were always made, approaching the point of extinction twice from opposite directions, and all values of C are the means of four such settings.

[1] Wied. Ann., vol. 39, no. 4, 1890, pp. 481 et seq.

The determining of ψ is a matter of more difficulty than that of Δ, and, in addition, the value of n is more affected by a small change in ψ than in Δ. The value of 2ψ required by the formula was obtained directly, as Drude did it, by rotating the polarizer through 90° and taking the difference of the corresponding settings of the analyzer. Every value of 2ψ is the mean of four settings, as with the values of Δ.

Current was supplied to the test piece by a small spring clip, the jaws of which were insulated from each other. Wires ran from these jaws through a rheostat, an ammeter and a knife switch to a dynamo. The jaws of the clip were made to clasp either the upper and lower or the right and left edges of the mirror, according as the current was to flow vertically or horizontally over the mirror. When horizontal, the (conventional) direction of the current was always from the side of the mirror nearest the collimator to that nearest the telescope.

The most difficult part of an absolute measurement of the index of a metal is to attain a perfect polish without contaminating the surface. For a relative measurement such as the present one it is not necessary to spend the great amount of time and trouble necessary to remove the last fine scratches. The polishing was done, first by a new file, then by successively finer grades of emery paper, ending with 000 of the French variety. This gave a polish, which, while not perfect, gave a value of the index reasonably near that found by Drude, who found it necessary to use 0000 paper and follow this with a steel burnisher. All operations of polishing were executed dry, and in a single direction.

A complete determination of the index was made under each of four conditions: (1) At the temperature of the room, and no current flowing; (2) with a current passing horizontally; (3) with a current passing vertically; (4) warmed by the passage of a current, throwing off the current immediately before the final setting of the compensator or nicol was made. The purpose of this was to distinguish between a true current effect and any effect due to the heat generated by the current. Drude remarks that he found the index to be independent of the temperature. In this he was in accord with the results of Sissingh, but Kundt found the reverse to be true.[1]

[1] Drude, Wied. Ann., loc. cit., p. 538.

Laue and Martens, however, find no certain alteration for a change of some 700°.

Following Drude's notation, the subscript 1 will be affixed to all measurements made with the residual scratches on the mirror parallel to the plane of incidence of the light, and the subscript 2 to those made with the scratches perpendicular to this plane.

The system of observing followed was to make one complete measurement of the index under each of the four conditions above described at a single setting. This could be done in about an hour after the polishing of the mirror had been effected, and in this time no marked change of the surface took place, as is shown by the fact that the compensator readings, which are quite sensitive to surface impurities, were nearly the same at the end of the hour as at the beginning. To eliminate completely any effect of this kind the necessary observations were made in position 1 for all the four conditions successively, and then, placing the mirror in position 2, the other half of the measurements were executed in reverse order of the conditions, thus ending under the same conditions as at first. As the mean of these two sets of results is used in the calculation of the index, it will be seen that this method of procedure ought to eliminate any uniform change in the nature of the surface.

To indicate more clearly the method of taking the observations, and also to give some idea of the degree of precision attainable the full record of one determination of the index will be given, selected at random, and then the results of the whole series will be compactly summarized.

Zero point of compensator -0.53
55
55 $\qquad \varphi = 72°$
55
-0.55

Current 10 amperes, vertical.

$C_1 = 1.78$
79
82
82

Set compensator at 1.81 and take readings of analyzer.

313° 35′
315 15
313 50
314 35
314° 19′

Turn polarizer 90° and read analyzer again.

234° 35′
235 00
234 35
234 40
234° 43′

$2\psi_1 = 314° 19' - 234° 43' = 79° 36'.$

Set mirror in position 2, and repeat measurements.

$C_2 = 1.82$
80
83
84

Set compensator at 1.82

Read analyzer.

237° 50′
236 55
238 10
237 25
237° 35′

Turn polarizer 90° and read analyzer again.

314° 30′
314 15
314 45
314 5
314° 24′

$2\psi_2 = 314° 24' - 237° 35' = 76° 49'.$

$$C = \frac{C_1 + C_2}{2} + 0.55 = 2.37,$$

$$\Delta = 36.18C = 85° 45',$$

$$2\psi = \frac{2\psi_1 + 2\psi_2}{2} = 78° 13',$$

$$n = 0.557.$$

Table of Values of n.

Cold.	Warm.	Current Horizontal.	Current Vertical.
0.578	0.578	0.529	0.567
554	557	549	583
539	547	540	516
551	550	551	569
555	550	564	568
568	529	583	546
532	563	547	569
517	513	535	543
589	575	591	575
552	589	554	563
554	593	563	557
518	497	536	514
Mean 0.551	0.553	0.554	0.556
Average departure from mean 0.016	0.023	0.015	0.017

In all the above results $\varphi = 72°$ and the current, where applied, was nearly 10 amperes. The cross-section of the mirror being 0.2 sq. cm., the current density was about 50 amperes per square centimeter. The third figure of these results is uncertain, but it may safely be said that there is no variation as great as one unit of the second figure, that is, about two per cent. of the whole.

Drude's value for electrolytic copper with the mirror face parallel to the electrode is 0.687. This greater value is due to two reasons :

The above values of n were calculated by means of the formula already quoted from Drude's Theory of Optics, which is approximate, and not rigid. Drude's value was calculated by means of a formula giving a closer approximation,[1] the effect of which, if applied to my values, would increase the second figure by three units. The simpler formula is, however, sufficient for the purpose of a relative measurement. The imperfection of the polish may possibly account for the remainder of the difference.

The work of Laue and Martens previously referred to was an attempt to determine the optical constants of glowing platinum by the polarization of the obliquely emitted radiation. For a strip of platinum heated to glowing, presumably by a current, although

[1] Drude, Wied. Annalen, loc. cit., p. 507, formula 3. Formula 4 is the equivalent of the simpler form given in his Theory of Optics.

this is not expressly stated in the paper, they obtained for the index of refraction nearly 2.9. Drude's value for cold platinum is about 2.1. The authors consider it probable that this difference was not due to change of temperature, as an alteration of some 700° in the latter produced no certain change in the index. Now this change of temperature must have been produced by varying the current in the strip; and by the same line of reasoning it would appear from the work of Laue and Martens that the index is independent of the current. The difference between their result and that of Drude must therefore be ascribed to some cause other than heat or the current. Possibly it may be found in the severe chemical treatment to which they subjected the platinum surface preparatory to the measurement.

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THE CRYSTALLIZATION OF UNDERCOOLED WATER.

By Boris Weinberg.

IN order to show the undercooling of water and to allow the free development of its crystals I endeavored to introduce into the overcooled water a piece of ice put in a finely drawn out glass tube. The experiment, carried out the first time by Mr. Michael Twanow, gave an unexpected result. When the crystallization attained the end of the tube there began to grow at this point an ice crystal having the shape of a hexagonal star and very similar to the characteristic snow-crystals.

The greater the undercooling of water the more numerous were the ramifications and the greater the velocity of crystallization. With water overcooled to at emperature between — 0°.3 and — 1° I obtained small stars with few narrow ramifications (Fig. 1). Undercooling to a temperature between — 1° and — 3° gave rise

Fig. 1.

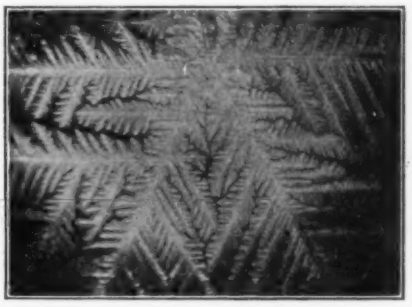

Fig. 2.

to stars with such dense ramifications that they resembled hexagonal plates (Fig. 2). The plane of the stars contains the direction of the end of the tube and therefore when this end is vertical a sufficiently large plate can divide the vessel into two parts. An undercooling greater than — 3° — especially when the end of the tube is not narrow enough — produces several plates set in different

azimuths, and the whole mass becomes at last a mixture of differently sized crystals and water, resembling the so-called "anchor ice."

The crystals are often a conglomeration of several stars which have their planes, their principal rays and even the ramifications of higher order parallel (Fig. 3).

If a star is broken, the pieces of it rise horizontally in the water with slight oscillations and attain the surface. This circumstance can explain the verticality of the optic axis by river and lake ice.

Fig. 3.

The evolution of these artificial snow crystals can be easily projected on a screen, if the vessel (a tumbler, an alembic, an evaporating dish) with undercooled water is put into another vessel with plane-parallel sides, containing water of a temperature somewhat higher than the thaw temperature of the surrounding air. For undercooling any water can serve, but the refrigerating mixture (finely chopped ice, upon which is poured a strong solution of NaCl) must not be too cold (from $-4°$ to $-6°$) and its level must be lower than the level of the water which is to be undercooled.

The projection is especially beautiful when the vessel is placed between two crossed nicols (the photographs of Figs. 1–3 are taken in this way; magnification 3×1). A star on a dark ground grows which gradually becomes more and more bright and at last — when thick enough (the thickness is generally of the order of a tenth of a millimeter) — shows the colors of chromatic polarization. One can prove that these crystals are optically uniaxial; if the tube is turned so that the plane of a star is at right angles to the rays of polarized light the image of the star disappears.

Precise measurements of these crystals will be made in winter when it will be possible to prolong their fugitive existence. The size of the stars depends — at a sufficient undercooling, *e. g.*, of $-2°$ — principally on the dimensions of the vessel with overcooled water. I often obtained single stars 8–12 cm. broad.

ST. PETERSBURG,
July, 1908.

DISTRIBUTED CAPACITY OF RESISTANCE COILS.

By S. Leroy Brown.

AN attempt has recently been made to construct a resistance coil, which would be free from inductance and capacity.[1] This coil was made of number 40 Advance wire, wound in a bifilar coil on a spool 12 cm. in diameter. The wires were twisted together and consecutive turns were 5 mm. apart. The twisting of the wires prevented the introduction of inductance by winding the wires into a coil. The separation of consecutive turns eliminated any measurable capacity that might be caused by the crowding of the wires into a compact coil. Therefore the inductance and the capacity of such coil are reduced to the inductance and the capacity of the two wires lying side by side. Measurements which were made with this coil showed that the preponderance of either inductance or capacity was too small to be measured. The capacity was increased by immersing the coil in petroleum, thereby increasing the specific inductive capacity of the medium between the wires, and still no capacity could be detected. The presumption that the capacity due to the adjacent wires in the bifilar turns of an ordinary resistance coil is only a small fractional part of its total capacity seemed to be justified. Therefore it was concluded that the inductance and the capacity of this so-called ideal coil had been effectively reduced below measurable quantities.

At the time when the description of this coil and its application to the investigation of the capacity of resistance coils appeared, the writer was working on a similar problem. The results which he had obtained indicated that there was an excess of capacity over inductance in such a coil which could be calculated and measured experimentally. A similar coil was immediately constructed, and it is the purpose of this paper to show, both by calculation and by experiment, that it is not free from capacity.

The coil constructed by the writer was made of two number 35

[1] A. H. Taylor and E. H. Williams, Phys. Rev., June, 1908.

double silk-covered german silver wires, soldered together at one end. These were twisted together and wound on a rectangular block 11 cm. by 12 cm. in section. The length of the bifilar winding was 2,750 cm., the wire having a resistance of 1,000 ohms. The distance between consecutive turns was about 4 mm. By the aid of a microscope, the distance between the wires in the bifilar turns was determined to be 0.021 cm. In some places, however, where the pressure between the wires was sufficient to deform the covering, the distance between the centers of the wires was probably slightly less than 0.021 cm.

The standard used for comparison consisted of two straight, parallel wires, connected at one end. The idea underlying this construction was not to reduce either the inductance or the capacity below measurable quantities, but to place the wires at such a distance apart that the inductance may just balance the capacity, when an alternating electromotive force is applied at the terminals. The correct distance between the wires was determined by calculation and verified by experiment. The results obtained in verifying this standard showed that the distance between the wires could be so chosen that the error may be less than 5 micromicrofarads. That is, neither the excess of capacity over inductance nor the excess of inductance over capacity would amount to more than 5 micromicrofarads of capacity in parallel with the standard.

Comparison of the coil with the standard was made by means of a Wheatstone network of resistances, using a form of galvanometer described by Stroud [1] to obtain a balance in the bridge. This galvanometer proved to be very sensitive. A disturbance in balance produced by only a few micromicrofarads of capacity placed in parallel with a thousand ohm coil or by a few microhenrys of inductance in series with it could be detected. A constant alternating electromotive force is necessary to obtain the accuracy required in these measurements. The source of electromotive force used in this work was an inverted rotary converter, which was run by a storage battery. The frequency used was 40 cycles per second.

Measurements with the rectangular coil described above, showed a considerable excess of capacity over inductance. When the coil

[1] Stroud, Phil. Mag., VI., 1903.

was in air, 420 micromicrofarads of capacity were added in parallel with the standard to obtain a balance. The coil was immersed in petroleum and 685 micromicrofarads of capacity were required in parallel with the standard to effect a balance. After removing the coil from the petroleum bath, but with the covering on the wires still moistened with oil, the capacity measured 585 micromicrofarads. This value is between the values obtained when the coil was in air and when it was in oil. The capacities which were added to obtain a balance between the coil and the parallel wire standard were made of rectangular sheets of tinfoil, separated by a plate of glass. The capacities could thus be determined approximately by calculation.

Assuming unit specific inductive capacity of the dielectric between the wires and that the distance between centers is 0.021 cm., the excess of capacity over inductance is 355 micromicrofarads, by calculation. If petroleum is assumed as the dielectric, the excess of capacity is about 800 micromicrofarads. This value is to be compared with the value 685 micromicrofarads obtained experimentally. It is to be expected that these values would differ, since the medium between the wires was not entirely composed of petroleum. The experimental value of 685 micromicrofarads was obtained with a dielectric of petroleum and silk and the value 420 micromicrofarads with a dielectric of air and silk. The discrepancy between calculated and experimental values may thus be accounted for.

It is the opinion of the writer that a comparison coil, made as described by twisting the wires together, is not sufficiently accurate when the magnitude of the capacity to be measured is only a few hundred micromicrofarads. It is to be noted, however, that the capacity of the 1,000-ohm coil, made of number 40 wire, is smaller than the value given above for a coil of number 35 wire, since the length of the wire in the former is less. The exact distances between the wires, as well as the lengths of the wires in the two coils, must be known in order to compare their capacities numerically, but it is evident that the capacity of neither is negligible when such small capacities are measured.

The capacities of the 1,000- and 2,000-ohm coils of resistance box number 3,187, made by Otto Wolff, of Berlin, were measured by comparison with the parallel wire standard. The coils are made

of rather large wire, wound on brass cores and heavily coated with shellac. The 1,000-ohm coil showed a capacity of about 750 micro-microfarads, and the 2,000-ohm coil about 1,140 micromicrofarads. These values are seen to be higher than those found by A. H. Taylor and E. H. Williams [1] for similarly described coils. They found 549.4 to be an average value for the 1,000-ohm coils of Wolff boxes numbered 2,894, 2,896, 2,897, 2,898, 2,899, 2,900 and 2,615; and 621 micromicrofarads to be an average value for the 2,000-ohm coils of Wolff boxes numbered 2,615 and 2,897.

A complete description of the parallel wire standard and the galvanometer used in this experiment, together with their application to the measurement of the distributed capacity of resistance coils will be given in a future paper.

UNIVERSITY OF CALIFORNIA,
September, 1908.

[1] PHYS. REV., June, 1908, p. 417.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

MINUTES OF THE FORTY-THIRD MEETING.

THE fall meeting of the Physical Society was held at Columbia University, New York City, on Saturday, October 24, 1908, with President Edw. L. Nichols in the chair.

The following papers were presented:

1. Note on Spherical Aberration. W. S. FRANKLIN.

2. New Photometric Methods of Studying the Radiating Properties of Various Substances. EDWARD P. HYDE.

3. Sparking Potentials in a Very High Vacuum. R. A. MILLIKAN.

4. Non-Newtonian Mechanics. GILBERT N. LEWIS.

5. The Definition of a Perfect Gas. A. G. WEBSTER and M. A. ROSANOFF.

6. The Specific Heats of Gases and the Partition of Energy. [By title.] W. P. BOYNTON.

7. The Distribution of Sound from the Megaphone. A. G. WEBSTER.

8. The Reflection of Sound by the Ground. A. G. WEBSTER.

9. Thermometric Lag in Calorimetry. [By title.] WALTER P. WHITE.

10. The Electromagnetic mass of a General Electric System. D. F. COMSTOCK.

11. A Study of Electric Wave Vibrators and Receivers. H. W. WEBB.

12. Note on a Method of Determining the Concentration of the Free Electrons in a Metal. O. W. RICHARDSON.

13. The Kinetic Energy of the Positive Ions Emitted by Hot Bodies. F. C. BROWN.

14. A Second Order Force on Moving Molecules. [By title.] D. F. COMSTOCK.

ERNEST MERRITT,
Secretary.

THE SPECIFIC HEATS OF GASES AND THE PARTITION OF ENERGY.[1]

BY W. P. BOYNTON.

THE underlying idea of the kinetic theory of gases is that heat energy is different from other manifestations of mechanical energy only in that it is associated with portions of matter too small for direct experi-

[1] Abstract of a paper presented at the New York meeting of the Physical Society, October 24, 1908.

mental observation. In accordance with this idea the energy, commonly called the heat, which raises the temperature of any substance may contribute to its kinetic energy or to its potential energy or may do external work; the external work is recognized in the case of a gas as constituting the difference between its specific heats at constant volume and at constant pressure. The kinetic energy is usually classified as either translational, rotational or vibrational; and as a first approximation the kinetic theory of gases assumes that all the molecular energy is that associated with translation. The further assumptions of Avogadro's law and of Maxwell's doctrine that temperature equilibrium corresponds to equality in the mean kinetic energy of translation of the molecules results in the view that the heat capacities of different gases per gram-molecule should be the same, a view which is partially substantiated by the facts.

The work of Dulong and Petit showing the near-constancy of the atomic heats of elements in the solid form has led to the attempt to find a similar law among gases, which do indeed fall into certain well-defined groups when so studied; extensive tabulations are given for instance in Winkelmann's Handbuch der Physik.[1]

The fundamental principles just mentioned may be used to secure results more consistent than those commonly quoted, and apparently more rational. As has been stated, it seems probable on theoretical grounds that temperature corresponds to the mean molecular kinetic energy of translation; but the heat-capacity of a gas at constant volume evidently involves also the energy capacities associated with the rotations and vibrations of the molecules, and with their internal potential energies. The last cannot be prophecied, but are sometimes negligible; Jeans has shown that the vibrational energy is associated with radiation, and that this portion of the energy may be small at ordinary temperatures. The equilibrium between evaporation and condensation which gives rise to the definite saturation densities and pressures of vapors suggests an analogous equilibrium in the mutual transfer of energy between the translational and rotational phases, with a corresponding definite ratio between the amounts of energy associated with these phases. One attempt to give numerical values of this ratio based upon theoretical considerations is the Maxwell-Boltzmann doctrine of the equipartition of energy between the different "degrees of freedom" of the molecules; according to this law the energy of a monatomic gas should be entirely translational, while in the case of a diatomic gas 3/5, in a gas made up of rigid polyatomic molecules 3/6, in one of the loosely hinged triatomic molecules 3/7, and in the case of more complex loosely hung molecules a still smaller fraction of the energy should be translational. These figures lead to the classical values of the ratio of the two specific heats, $1\frac{2}{3}$, $1\frac{2}{5}$, $1\frac{2}{6}$,

[1] 1st ed., II., 2, pp. 387–393; 2d ed., III., pp. 225–237.

$1\frac{2}{7}$, etc. In a previous paper[1] I have shown that such properties as are taken into account in an equation of state, like that of van der Waals, will explain small variations in either direction from these simple values; but the consumption of energy in vibrational motion or in potential energy will reduce the fraction of the total energy which is translational, and also the value of the ratio of the two specific heats. On the other hand, the ratio of the two specific heats gives us a means of computing the ratio of translational to total energy, for if H be the total and K the translational energy then

$$\frac{C_p}{C_v} = \gamma = 1 + \frac{2}{3}\frac{K}{H}$$

and

$$K/H = 3/2\,(\gamma - 1).$$

In the following tabulations data are taken, with the exception of argon, from Winkelmann.[2] I have not been able to secure figures on the specific heats of other monatomic gases, or of gases with triangular or other rigid structure. Magie[3] in a discussion somewhat related to this gives the value .9886 for the molecular energy-capacity in calories per degree C. per degree of freedom, which leads to the value 2.9658 for the translational part of the molecular heat; this is figured not from thermal data, but from the "mean square" velocity for hydrogen. The gases are grouped in four tables according to their complexity. The columns give (1) the name, (2) formula, (3) molecular weight, (4) ratio of specific heats, (5) specific heat at constant volume, (6) "molecular" heat found by multiplying (3) and (5), (7) the "atomic" heat found by dividing (6) by the number of atoms in the molecule, (8) the ratio K/H derived from the ratio of the specific heats, (9) the "translational" energy capacity, found by multiplying (6) and (8).

TABLE I.

MONATOMIC GASES.

Computed Values, $\gamma = 1.667$. $C_v m = 2.9658$.

1 Name.	2 Formula.	3 M. Wt.	4 γ	5 C_v	6 $C_v m$
Mercury.	Hg	200	1.666	.0147	2.94
Argon.	A	39.9	1.667	.07405	2.96

[1] PHYS. REV., XII., pp. 353–358, 1901.
[2] Loc cit.
[3] Science, XXIII., pp. 161–178, 1906.

TABLE II.

DIATOMIC GASES.

Computed values, $\gamma = 1.4$, $C_v m = 4.943$.

1 Name.	2 Formula.	3 M. Wt.	4 γ	5 C_v	6 $C_v m$	7 At Ht.	8 K/H	9
Air.		28.86	1.405	.172	4.96	2.48	.607	3.01
Oxygen.	O_2	32	1.405	.1544	4.95	2.47	.607	3.00
Nitrogen.	N_2	28	1.405	.1735	4.86	2.43	.607	2.95
Hydrogen.	H_2	2	1.405	2.4263	4.85	2.43	.607	2.94
Carbon monoxide.	CO	28	1.403	.1746	4.89	2.44	.604	2.95
Nitric oxide.	NO	30	1.394	.1662	4.99	2.49	.591	2.95
Hydrochloric acid.	HCl	36.5	1.394	.1392	5.08	2.54	.591	3.01
Hydrobromic acid.	HBr	81	1.431	.0573	4.64	2.32	.646	2.99
Hydriodic acid.	HI	128	1.397	.0394	5.04	2.52	.595	3.00
Chlorine.	Cl_2	71	1.323	.0873	6.20	3.10	.484	3.00
Bromine.	Br_2	160	1.292	.0428	6.84	3.42	.438	3.00
Iodine.	I_2	254	1.307	.057	6.52	3.26	.460	3.00
	ClI	162.5	1.317	.0389	6.32	3.16	.475	3.00
	BrI	207	1.33	.029	6.14	3.07	.495	3.04

TABLE III.

TRIATOMIC GASES.

Computed values, $\gamma = 1.2857$, $C_v m = 6.9202$.

1 Name.	2 Formula.	3 M. Wt.	4 γ	5 C_v	6 $C_v m$	7 At Ht.	8 K/H	9
Nitrous oxide.	N_2O	44	1.311	.1513	6.66	2.22	.466	3.11
Carbon dioxide.	CO_2	44	1.311	.1486	6.54	2.18	.466	3.05
Hydrogen sulphide.	H_2S	34	1.258	.1933	6.57	2.19	.387	2.54
Water.	H_2O	18	1.306	.3637	6.56	2.19	.459	3.01
Sulphur dioxide.	SO_2	64	1.248	.1237	7.92	2.64	.372	2.95
Carbon disulphide.	CS_2	76	1.200	.1312	9.97	3.32	.300	2.99

CONCLUSIONS.

The following statements are offered, based largely upon the facts here presented.

1. The ordinary statement of the doctrine of equipartition assumes that all the energy received is stored as kinetic energy and that all the collisions are such as to lead to a state of equilibrium between the different "degrees of freedom" or "momentoids." In a few cases of simple "permanent" gases this fairly represents the facts. The non-integral values found for the number of degrees of freedom by Magie[1]

[1] Loc. cit.

TABLE IV.

POLYATOMIC GASES.

1 Name.	2 Formula.	3 M.Wt.	4 γ	5 C_v	6 $C_v m$	7 At Ht.	8 K/H	9
Ammonia.	NH_3	17	1.317	.3803	6.46	1.62	.470	3.04
Phosphorus trichloride.	PCl_3	137.4	1.122	.1200	16.49	4.12	.183	3.02
Arsenic trichloride.	$AsCl_3$	181.4	1.110	.1011	18.34	4.59	.165	3.03
Marsh gas.	CH_4	16	1.319	.4495	7.19	1.44	.478	3.44
Chloroform.	$CHCl_3$	119.4	1.118	.1403	16.81	3.36	.177	2.98
	$SiCl_4$	169.8	1.097	.1211	20.56	4.11	.146	3.00
	TCl_4	189.8	1.087	.1162	22.05	4.41	.131	2.88
	$SnCl_4$	259.8	1.087	.0864	22.45	4.49	.131	2.93
Methyl Alcohol.	CH_4O	32	1.159	.3950	12.64	2.11	.239	3.00
Ethyl alcohol.	C_2H_6O	46	1.107	.4078	18.76	2.08	.161	3.02
Cyan-ethyl.	C_3H_6N	56	1.093	.3892	21.80	2.18	.140	3.04
Brom-ethyl.	C_2H_5Br	109	1.113	.1631	17.78	2.29	.170	3.02
Ethyl sulphide.	$C_4H_{10}S$	90	1.058	3785	34.04	2.27	.087	2.97
Ether.	$C_4H_{10}O$	74	1.060	.4540	33.59	2.24	.090	3.02
Acetic ether.	$C_4H_8O_2$	88	1.060	.3781	33.27	2.37	.090	2.99
Aceton.	C_3H_6O	58	1.090	.3783	21.94	2.19	.135	2.96
Ethylene.	C_2H_4	28	1.245	.2702	7.57	1.26	.367	2.72
Ethylene chloride.	$C_2H_4Cl_2$	98.9	1.109	.2093	20.44	2.55	.164	3.35
Benzol.	C_6H_6	78	1.073	.3467	27.17	2.26	.110	2.98
Turpentine.	$C_{10}H_{16}$	136	1.030	.4914	66.83	2.57	.045	3.01

and others is to be accounted for by the absorption of potential energy, or of kinetic energy of a non-equilibrating type, *e. g.*, vibrational; preferably the former.

2. The attempt to find "atomic" heats for gases is apparently a mistake; the few gases which give consistent results are either very simple, those formerly classed as the permanent gases, or else mon-atomic, and in either case give consistent results however studied. Column (7) shows variations too large to be explained as experimental error.

3. Specific heats can be computed for the simpler gases from purely mechanical data and the simple ratios of degrees of freedom with considerable accuracy; for instance, nitrogen is diatomic and has the molecular weight 28. Taking from Table II. the computed value $C_v m = 4.943$, $C_v = 4.943/28 = .1764$, observed value .1735, a difference of about 2 per cent.

4. The numbers in the last column, (6) for monatomic, (9) for polyatomic gases, show a uniformity which is gratifying though not surprising. Out of forty gases and vapors only four show considerable variations, and of the remainder only one shows a variation exceeding 3 per cent. This ought in many cases to be well within the experimental error. It is notable that the results are equally consistent for simple gases, for

those with complex molecules which have seemed hitherto to defy prophecy, and for the halogens whose abnormal specific heats are explained by Magie as due to "internal" degrees of freedom and by others as due to an absorption of potential (latent) energy due to approaching dissociation.

A reversal of the process we have employed enables us to compute the specific heats of *any* gas from a knowledge of its molecular weight and the ratio of the two specific heats. A few results are given for familiar substances.

TABLE V.

Computed Specific Heats.

Substance.	C_v Computed.	C_v Observed.	Difference.	Per Cent.
Nitrogen.	.1744	.1735	.0009	.5
Water.	.3589	.3637	.0048	1.3
Carbon disulphide.	.1298	.1312	.0014	1
Ethyl alcohol.	.4000	.4078	.0078	2

The conclusions here reached seem perfectly obvious, as they are involved in the constancy of the difference between the molecular heats at constant pressure and volume, a fact long recognized, but the prevalence of the presentation of atomic heats in standard texts has seemed to justify this discussion which has been intended to emphasize what the writer believes to be a more rational point of view.

UNIVERSITY OF OREGON,
April 25, 1908.

A STUDY OF ELECTRIC WAVE VIBRATORS AND RECEIVERS.[1]

BY HAROLD W. WEBB.

THIS study was undertaken to determine the dimensions and conditions for electric-wave vibrators and receivers corresponding to any given wave-length. The investigation was based on wave-length measurements by the Boltzmann two-mirror method. As the determination of the resonance length of a receiver by tuning was found unreliable, a non-selective receiver, consisting of a Klemencic receiver of ten or more times the length for resonance, was used in place of the usual tuned receiver. Considerable difficulty was experienced because of the disturbing action of the collecting mirrors behind the vibrator and the receiver, but this was eliminated by averaging the results for a number of different vibrators.

[1] Abstract of a paper presented at the New York meeting of the Physical Society, October 24, 1908.

A vibrator of cylindrical form was studied and it was found that if the relative dimensions were maintained constant the wave-length emitted was directly proportional to the dimensions. With the relative dimensions: length $= 8 \times$ diameter $= 16/3 \times$ length of supporting dielectric at the center, the wave-length was 2.4 times the length of the vibrator. Starting with this vibrator as a standard the effect of varying the conditions was determined. The length of the dielectric, and the ratio of the diameter to the length were found to influence the wave-length.

A modified form of Righi vibrator was studied in a similar way.

The receivers in resonance with given wave-lengths were investigated. For this purpose a standard form with constant relative dimensions was selected. Wave-length measurements were substituted for the usual tuning curves in this study, as they were found much more satisfactory. The length of receiver giving a wave-length equal to the wave-length determined by the non-selective receiver was taken as the resonating length. The effect on this length of varying the conditions was studied. The width and thickness of the flat antennæ used, the length of the supporting dielectric at the center, and the length of the constriction at the thermo-junction, were found to be important factors.

The limiting value of the ratio between the length of the vibrator and the emitted wave-length as the diameter approached zero was 2.24. With a receiver of very small diameter the value 2.22 was determined as the relation between the length of receiver and the corresponding wave-length.

New Photometric Methods of Studying the Radiating Properties of Various Substances.[1]

By Edward P. Hyde.

THE recent development of high efficiency metallic filament lamps has aroused new interest in the measurement of the high temperatures of glowing metals, and has raised the question as to whether the high efficiencies are due primarily to the high temperatures at which the filaments operate, or to a selective radiation, where by selective radiation is meant that the distribution of the energy in the spectrum of the radiating body at a given temperature is different from that of a black body at the same temperature.

A recent photometric study of the relative properties of the newer metal, and the older carbon filament lamps has led to the establishment of two new photometric methods by which a positive qualitative criterion may be had of relative selectivity of two radiating filaments. According

[1] Abstract of a paper presented at the New York meeting of the Physical Society, October 24, 1908.

to the first method if one filament is maintained at some definite voltage or current (*i. e.*, at some definite temperature) and the voltage of a second filament is changed until the distribution of energy in the visible spectra of the two as determined by a spectrophotometer is the same, then if the two filaments had identical radiating properties the energy curves of the two would be identical throughout the entire spectrum, and the temperatures of the two filaments would probably be the same. If this were the case, the ratio of the energy in the visible spectrum to the total energy radiated would be the same for the two filaments. Now the energy radiated in the visible spectrum can be measured by determining the mean spherical candle-power, and the total energy radiated can be determined by measuring the energy input, since there is no convection and very little conduction.

If the radiating properties of the two filaments were identical, the watts per mean spherical candle under the above conditions would be the same for the two filaments. Conversely if under the above conditions the watts per mean spherical candle are different, one of the filaments must be radiating selectively with respect to the other.

According to the second method the two filaments are brought to the same distribution of energy in the visible spectrum in the same way as that employed in the first method. If, now, a determination is made of the percentage change in candle-power corresponding to one per cent. change in energy supplied to the lamp for each filament, these two coefficients of change of candle-power corresponding to one per cent. change in energy would be the same if the radiating properties of the two filaments were identical. Conversely if the two coefficients are different one filament must be radiating selectively with respect to the other.

In the actual use of these two methods the determination of the agreement in the visible spectrum of the energy curves of the two filaments has been made, not with a spectrophotometer as described above, but by means of a color match in an ordinary Lummer-Brodhun contrast photometer. If one lamp is maintained at some definite voltage and the voltage of a second lamp is changed until the color of the light radiated by the two lamps is the same, as observed in the photometer, it has been found that the spectrophotometric curves of the two filaments agree excellently. The color-match method is simpler and perhaps even more exact than the spectrophotometric method, provided there is no strong selectivity within the visible spectrum.

By the use of the above two methods interesting results have been obtained on the radiating properties of various filaments.

The Electromagnetic Momentum of a General Electric System.[1]

By Daniel F. Comstock.

At the present stage in the development of physics when we have so much reason to believe that the atoms are electric systems, while we have almost no knowledge as to the particular structure of these systems, it becomes of great interest to know if there are any results which can be obtained from general electric theory without any special assumptions as to special structure.

The author has shown before that within certain limitations the electromagnetic mass of a system may be expressed as a function of its total contained energy.

The following is an outline of a chain of reasoning which assumes *nothing* but the equations of the Maxwell-Lorentz theory and gives as a result an expression which applies to *any* electromagnetic system. The chief difficulty in the general problem is that the "velocity of the whole system" has *a priori* no definite mathematical meaning, inasmuch as an electromagnetic system cannot be said to have a center of gravity in the simple mechanical sense. The expression obtained below shows clearly what must be taken as the velocity of the system if the result is to have simple meaning.

For brevity I use vector notation, the operation symbols used being those of Abraham and Föppl's "Theorie der Elektrizität."

The following symbols for the various quantities are used:

W = density of total electromagnetic energy.
E = electric force intensity.
H = magnetic force intensity.
C = velocity of light.
S = Poynting vector.
M = density of electromagnetic momentum.
v_1 = velocity of the axes through space. (The axes are to move so as to remain parallel to themselves.)
v = velocity of the electric charge through space.
v_2 = velocity with respect to the moving axes.
$\beta = v_1/C$.
F = total electromagnetic force on unit charge.
σ = density of electricity in electrostatic units.
d/dt = time rate of change with respect to axes fixed in space.
$\partial/\partial t$ = time rate of change with respect to the moving axes.

Now from the conservation of energy

[1] Abstract of a paper presented at the New York meeting of the Physical Society, October 24, 1908.

$$\frac{dW}{dt} = -\text{div. } S - (vF)\sigma$$
$$= -\text{div. } S - C(\beta F)\sigma - (v_2 F)\sigma. \tag{1}$$

Also from the momentum principle (see Abraham, II., p. 25)

$$F_x\sigma = \frac{\partial X_x}{\partial x} + \frac{\partial X_y}{\partial y} + \frac{\partial X_z}{\partial z} - \frac{dM_x}{dt} \tag{2}$$

where

$$X_x = \frac{1}{8\pi}(E_x^2 - E_y^2 - E_z^2 + H_x^2 - H_y^2 - H_z^2),$$
$$X_y = \frac{1}{4\pi}(E_x E_y + H_x H_y), \tag{3}$$
$$X_z = \frac{1}{4\pi}(E_x E_z + H_x H_z).$$

There are also of course two other equations for the y and z components of F.

Making no further assumptions, except that the system is isolated, we can obtain the result

$$\int x \left\{ \frac{\partial W}{\partial t} + (v_2 F)\sigma - C\left(\beta \frac{\partial M}{\partial t}\right) \right\} d\tau = \int \left\{ C^2 M_x + \frac{C}{4\pi}\left[E_x(\beta E) + H_x(\beta H) - \beta_x(E^2 + H^2) + \beta(\beta\{EH\}) \right] \right\} d\tau. \tag{4}$$

and similar equations for x and y.

If the left-hand side of (4) is zero then the component of the total momentum in the direction of (β) is seen to be (since $M = 1/4\pi c[EH]$

$$M_\beta = \frac{2\beta}{C(1+\beta^2)} \int \left(W - \frac{E_\beta^2}{8\pi} - \frac{H_\beta^2}{8\pi} \right) d\tau. \tag{5}$$

Since the expression in the integral is obviously the part of the total energy which is represented by the components of the electric and magnetic forces at right angles to the direction of motion, we have the same expression for the momentum as was obtained in a previous paper.[1]

The condition for this to be true is that the integral on the left of (4) vanishes as well as the similar x and y integrals. A consideration of this integral will show that it represents a certain energy flow *through the system* together with a momentum flow. The moving axes can be taken so that the internal momentum flow, *i. e.*, transfer of momentum *through the system* is zero. If the energy flow integral is then zero the above result (5) is true.

[1] Phil. Mag., Jan., 1908.

Systems which satisfy this energy flow condition have a certain kind of symmetry, which closer analysis can easily make clear.

For systems which have average symmetry about a point the "transverse energy" is equal to two thirds of the total energy and the momentum is then proportional to the total energy.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY,
BOSTON, MASS.

NON-NEWTONIAN MECHANICS.[1]

BY GILBERT N. LEWIS.

TWO fundamental laws are assumed, the law of the conservation of momentum, and the law of conservation of mass. The mass which is associated with a given momentum is *defined* as equal to the momentum divided by the velocity of its propagation. The momentum (M) of a beam of light is known to be equal to the energy (E) of the beam, divided by the velocity of light (V). Hence by definition the mass (m) of a beam of light is E/V^2. Thus a body radiating energy loses mass in proportion. Now the fundamental assumptions require further that if a body loses energy in any other way than by radiation, it still must lose mass in the same proportion. The mass of a body is therefore a linear function of its total energy, according to the equation $dm = dE/V^2$.

If the mass of a body is a function of its energy, the mass of a body which is in motion and thus possesses kinetic energy is not the same as the mass at rest. One of the fundamental axioms of Newton is that the mass of a body is independent of its velocity. This axiom must now be abandoned and thus a more general or non-Newtonian mechanics is developed, which includes ordinary mechanics as a special type, valid only for small velocities.

The mass of a body is given as a function of its velocity by the equation

$$m = \frac{m_0}{(1 - \beta^2)^{\frac{1}{2}}},$$

where m is the mass at rest and β is the ratio of the velocity to the velocity of light. This formula agrees with the experiments of Kaufmann on the mass of an electron, and is identical with the equation developed by Lorentz for the electromagnetic mass from the electromagnetic theory. The new equation for kinetic energy is

$$E = mV^2[1 - (1 - \beta^2)^{\frac{1}{2}}].$$

Thus the kinetic energy varies between $\frac{1}{2}mv^2$ at small velocities and mv^2 at the velocity of light. A moving body subject to a force (f)

[1] Abstract of a paper presented at the New York meeting of the Physical Society, October 24, 1908.

along the line of motion changes both in velocity and mass. The equations are

$$\frac{dv}{dt} = \frac{f}{m}(1 - \beta^2); \quad \frac{dm}{dt} = \frac{f}{v}\beta^2.$$

The longitudinal and lateral acceleration of a moving body under the influence of the same force has a ratio of $1 - \beta^2$. In a similar way all the equations of non-Newtonian mechanics may be derived from those which have been given.

THERMOMETRIC LAG IN CALORIMETRY.[1]

BY WALTER P. WHITE.

JAEGER and von Steinwehr have shown that in calorimetry by the method of mixtures, as usually conducted, an error very appreciable in refined work may arise through the lag of the thermometer. Richards, Henderson and Forbes have independently devised an elaborate calorimetric method (keeping the jacket temperature equal to that of the calorimeter) a main object of which is to avoid this error. Jaeger and von Steinwehr, however, maintain that the same result is far more easily reached by the simple correction which they give. This correction in its turn appears to require some modification; as given, it may often actually increase the error.

Jaeger and von Steinwehr's correction may be simply found as follows: If the thermometer lags L seconds behind the true temperature of the calorimeter, then that true temperature will equal the one read, plus the change of the calorimeter temperature in the time L. This change will be different for the initial and final temperatures, since the cooling rate will not be the same for each. The algebraic difference of the two changes, which is the correction itself, will therefore equal the time L, times the cooling constant, times the difference of the initial and final temperatures, that is, the temperature interval measured. (Jaeger and von Steinwehr's formula is $U \cdot a/b$, where U is the interval, a the cooling constant of the calorimeter, b, that of the thermometer.)

The error in this formula appears at once if the thermometric lag is treated as primarily a time phenomenon, which of course it really is. For if all the readings are equally affected by lag, the result is the same as if they had been taken without lag, but L seconds earlier. And since the exact instants at which the readings are made are not important as long as the time *intervals* are correctly recorded, there is in this case no thermometric lag error at all. The fallacy in the previous result enters as follows: The initial and final temperatures are separated by an interval

[1] Abstract of a paper presented at the New York meeting of the Physical Society, October 24, 1908.

of rapid temperature change, whose position in time affects the cooling correction, and has the same importance as that of the initial or final temperature. The ignoring of this interval in the above demonstration really involves the (usually false) assumption that its temperatures are not affected by lag while the others are. The formula should contain instead of the lag of one thermometer the difference of the lags of the one used for the initial and final, and that used for the intermediate temperatures. If one of these is an electric thermometer of negligible lag, and the other a mercurial (as in Jaeger and von Steinwehr's work), it is the lag of the latter which counts; if the same thermometer is used throughout, the correction (barring second-order effects) is zero, and then, as far as lag is concerned, Richards, Henderson and Forbes's method is unnecessary, and Jaeger and von Steinwehr's erroneous.

It follows that the importance of lag in calorimetric thermometers has been greatly overestimated.

The above reasoning, while ordinarily eliminating one lag correction, introduces another, hitherto generally overlooked, but readily appreciated as soon as the importance of lag during the middle interval is seen. For the loss of heat from a calorimeter depends on the temperature of the external surface. But when the water is being heated rapidly by a hot body within, the external surface ordinarily lags appreciably behind the thermometer which is used to determine the cooling correction. The resulting error is often greater than that due to simple thermometric lag. It is, moreover, difficult to determine and is of course not avoided by the method of Richards, Henderson and Forbes. It is thus one of the most intractable of calorimetric corrections, but like other lag corrections it can be eliminated (in a directly calibrated calorimeter) if the rate of stirring and some other factors are kept constant.

Under these conditions the lag in the cooling rate itself which is suspected by Richards, Henderson and Forbes could at the same time be eliminated in most cases. A need for their method, however, might still sometimes arise; if, for instance, the lag in the cooling correction should prove unexpectedly troublesome, or if there should be an error due to the lag within solid objects inside the calorimeter. The necessary reduction in the cooling rate might also be obtained — though at the cost of an increase in the required thermometric sensitiveness — by increasing the size of the calorimeter (and also, of course, for reasons independent of the question of lag, and therefore outside the scope of the present paper).

GEOPHYSICAL LABORATORY,
CARNEGIE INSTITUTION OF WASHINGTON,
September, 25, 1908.

A SECOND-ORDER FORCE ON MOVING MOLECULES.[1]

BY D. F. COMSTOCK.

WHEN a molecule moves through a magnetic field an observer traveling with it would notice an electric force. If the molecule is neutral and the magnetic force is uniform there is no resultant force on the molecule, but if the magnetic field is not uniform there is a force which can be shown to depend on the velocity and on the derivative of the magnetic force. When the velocity is taken in all directions, corresponding to a chaotic state, there is a force still left, toward the denser parts of the field, which is proportional to the square of the velocity. This gives the gas a fictitious paramagnetism.

Experiments are being started to detect this. The possible bearing on the second law of thermodynamics in its relation to kinetic theory is pointed out.

THE DEDUCTION OF THE CONCENTRATION OF THE FREE ELECTRONS INSIDE A METAL FROM PHENOMENA CONDITIONED BY THEIR EMISSION UNDER THE INFLUENCE OF HEAT.[1]

BY O. W. RICHARDSON.

THE loss of energy by a hot body arising from the emission of electrons, which was predicted and calculated theoretically by the author (Phil. Trans., A, Vol. 201, p. 503, 1903), has recently been detected experimentaly by Wehnell and Jentgsch (Verh. Deutsch. Phys. Ges., X. Jahr., p. 605, 1908). The present paper points out that measurements of this quantity, where they can be accomplished with sufficient accuracy, should enable the deduction by the method given by the author (Camb. Phil. Proc., Vol. 11, p. 286, 1901), of the number of free electrons per cubic centimeter inside a metal from the rate at which they are emitted at different temperatures, to be carried out in a manner which avoids serious uncertainties to which the method has hitherto been subject.

PRINCETON, N. J.,
October 23, 1908.

THE KINETIC ENERGY OF THE POSITIVE IONS EMITTED BY HOT PLATINUM.[1]

BY F. C. BROWN.

THE paper deals with investigation of the magnitude and the mode of distribution of the kinetic energy of the positive ions emitted by hot platinum.

[1] Abstract of a paper presented at the New York meeting of the Physical Society, October 24, 1908.

The method was the same as that used by Richardson and Brown for the negative ions. It consists in measuring the rate of charging up of a plate opposite a parallel plate containing a strip of hot metal, both plates being initially at zero potential. The ions from the hot metal cause the opposite plate to acquire a charge, the potential of which tends to stop further charging up. From the rate at which the current varies with the potential both the mean value of the kinetic energy and the way in which it is distributed among the different particles can be determined. A detailed description of the method has been given in the paper referred to above.

It was shown that where the distribution of velocity among the ions follows Maxwell's law the current to the plate being charged is expressed by

$$\log_e \frac{n}{n_0} = \log \frac{i}{i_0} = -\frac{\nu e}{R\theta} \cdot V$$

From the observations on the rate of charging up of the plate, curves were drawn showing the current against different potentials and the logarithm of the current against different potentials. The above equation was verified first in that the curves showing the logarithm of the current plotted againt potential were almost perfect straight lines and secondly in that the value of R calculated to be within the limits of experimental error the same as the constant R in the gas equation $pv = RT$. For three series of observations the results are given in the following table.

Series.	Air Pressure, mm.	Temperature Absolute.	Largest Current Amperes.	R	R From Equation $pv = RT$.
I.	28.0	1193	2×10^{-12}	3.9×10^{8}	
II.	15.0	1067	1.7×10^{-12}	3.5×10^{8}	
III.	0.009	1293	5×10^{-12}	3.5×10^{8}	
			Mean.	3.6×10^{8}	3.7×10^{8}

It follows that the mean kinetic energy of the positive ions emitted from hot platinum is the same as that of a molecule of a gas at the same temperature and also that the energy is to a certain extent independent of the pressure of the surrounding gas. The facts militate against the idea that the positive ions arise from chemical action, for in that case the kinetic energy would probably be increased or diminished due to the heat of reaction.

PRINCETON UNIVERSITY.

NEW BOOKS.

Thermodynamics: An Introductory Treatise dealing mainly with First Principles and their Direct Applications. By G. H. BRYAN. Leipzig, 1907, B. G. Teubner. Price, 7 marks.

This very interesting book has been developed from the same author's article in the "Enzyklopädie der Mathematischen Wissenschaften," and its fundamental idea is quite different from that of most previous works on thermodynamics. It treats the subject deductively, after the fashion of works on analytic mechanics, instead of working up according to a more or less historical sequence as the notions of thermodynamics have grown from experiment. To write a treatise of this sort for thermodynamics is very much more difficult than for the parallel case of mechanics. For it is much harder to give, in comprehensible form, the initial definitions of the quantities involved and to state the two fundamental principles clearly, without previous discussion of the experiments that have led to them, than it is to state Newton's laws of motion or whatever substitute for them is used as the starting point in dynamics.

The reviewer has long thought that thermodynamics was the hardest, because the most abstract, branch of physics he ever studied, and after reading the book before him he is quite sure of it. But this remark is by no means meant in an unfriendly sense. Such a philosophical review of the principles as one must take in reading this book is most salutary after one has gradually got some sort of familiarity with the historical and experimental development of the subject.

In order to lessen the shock of the plunge into deductive thermodynamics, the author has given in Part I., of only twenty-six pages, a very condensed elementary treatment of thermodynamics in the old-fashioned inductive style. This is, naturally, a mere selection of points that seem most important, and others may not think the selection the best possible; but everyone must admire the Spartan self-restraint with which the author has omitted all that seemed to him not essential and denied himself the pleasure of making all his statements rigorous and complete.

Part II. (chapters IV. to IX., pp. 29–96) constitutes the kernel of the book. It is devoted to a discussion of the two laws, the second being considered from the standpoint of the principle of the degradation of energy, though comparison is constantly made between this and the more usual methods of Clausius and Kelvin. Any competent discussion of

entropy and the second law is always welcome, and every advanced student of thermodynamics should read this one.

Part III., pp. 99–198, contains, in eight chapters, examples of the application of the principles already developed to various standard problems in physics and physical chemistry. The distinction between the deductive method and the old-fashioned inductive method ceases when the two laws have once been set forth, so that Part III. is more like what may be found elsewhere, though it is not lacking in originality. Chapter X., on radiation, might be improved, but it is something to find this most interesting and important subject considered at all.

Any detailed review of a book so short that everyone interested can afford to buy it and find time to read it is unnecessary and would be of use only to the reviewer. As an attempt to treat thermodynamics deductively the book is not a perfect success; but let anyone who thinks he can do better bring out his book; for a first try, this one is very excellent. The reviewer advises all teachers of theoretical thermodynamics to use this book, perhaps in conjunction with one of the other type, with their classes, as he intends to do himself when the opportunity presents itself.

Coming to matters of small detail; the book is on thin but substantial paper and of handy form. It is well printed and, in view of its having been printed in Germany, it is remarkably free from the typographical errors which so often make long tables of corrigenda necessary for German books. A few cases of rather odd use of words seem to have been due to confusion in a German mind of English words of somewhat similar sound and not very different meaning, and the author's use of moods and tenses is frequently somewhat capricious to say the least. However, such trifles do not diminish the scientific value of the work for they never interfere with the clearness of the thought, and the reviewer takes pleasure, in conclusion, in heartily recommending Professor Bryan's "Treatise" to all who are interested in theoretical physics.

EDGAR BUCKINGHAM.

NORTH SCITUATE BEACH, MASS.,
September 9, 1908.

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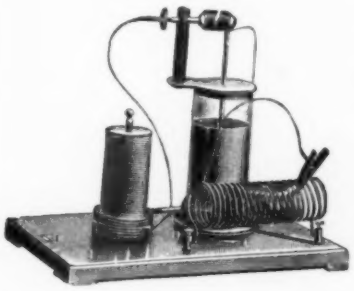

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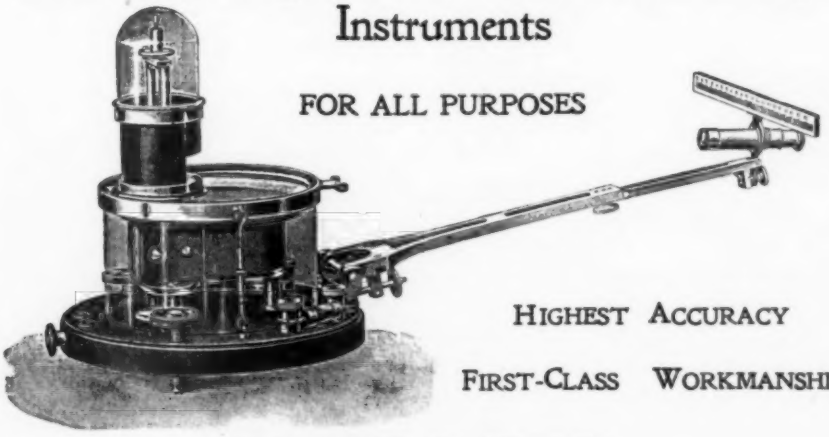

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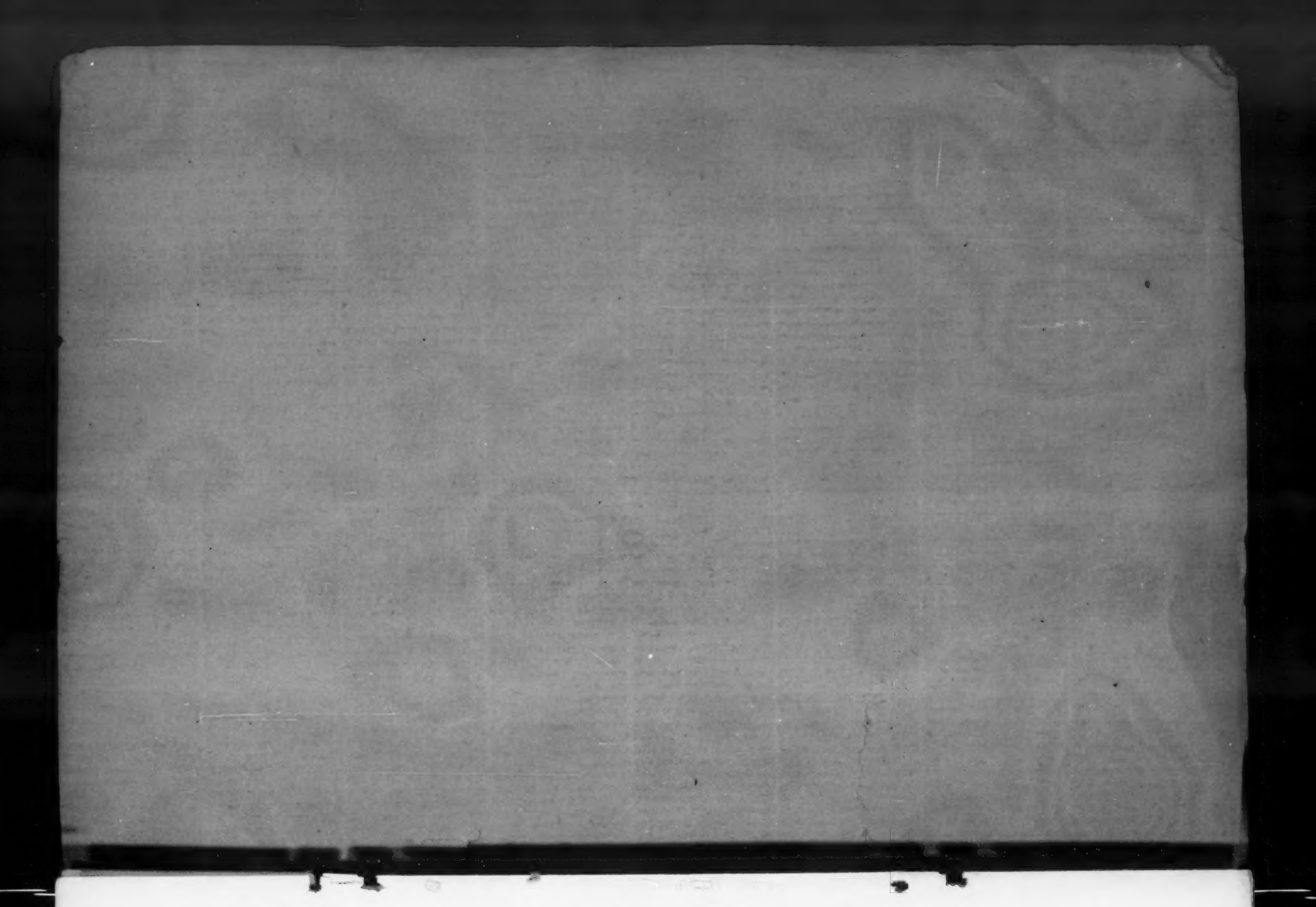

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